A DECISION MODEL FOR CHOOSING AMONG PHOTOVOLTAIC TECHNOLOGIES TO GENERATE ELECTRICITY AT GRID-CONNECTED AIR FORCE FACILITIES: A VALUE-FOCUSED APPROACH

THESIS

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Abstract

The United States is consuming fossil fuels faster than natural processes can replace them. Our nation's leaders recognize that a diverse energy portfolio including renewable energy is the key to maintaining our economy, security, and the environment. The federal government is by far the greatest energy consumer; thus, our nation's leaders have directed federal agencies to strive to increase the use of renewable energy at federal facilities. Solar electricity technologies, in the form of photovoltaics, have great potential in the renewable energy mix. Although a major strategy should be integrating photovoltaics into the design of new facilities, an important early consideration should be the installation of photovoltaic modules in open areas and/or module retrofits onto existing structures. This research developed a model based on decision makers' value systems to quantify and rank several photovoltaic technologies. The goal of the model was to determine what alternatives would most align with Air Force energy and environmental objectives. After working with subject matter experts at three bases, a comprehensive hierarchy was developed. This hierarchy was then used to find the best alternatives at one base. It was found that photovoltaic technologies may indeed successfully compete with grid-supplied electricity when utilizing a value-focused approach.

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To my Three Girls

Acknowledgments

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Mostyn O. Kellner

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1. Introduction

1.1. Background

1.1.1. The Carbon Cycle

The earth's energy system is not closed. The single, ultimate external input into the earth's system is the energy radiating from the sun. The sun drives all natural and man-made processes on the earth (Baker, 2000; Schmieder et al., 2004). Through photosynthesis, plants convert the sun's energy into glucose necessary for growth and reproduction. Plants then may either decay or be devoured by animals, which in turn, either die and decay or are consumed by higher order animals. In either case, the sun's energy, in the form of carbon, is trapped and preserved. Over millions of years, the decaying plants and animals decompose, and under pressure and heat, they become fossil fuels in the form of crude oil, natural gas, and coal. These fossil formations store energy indefinitely until the energy is released by incineration (Grassroots Marketing Alliance, 2003a). Figure 1 represents the carbon cycle. Man may tame plants and animals to some degree under the guise of agriculture and may extract the fossil energy from the earth to

use in industry. Regardless, agriculture and industry, the culmination of man's existence, are entirely dependent upon the sun's energy and the carbon cycle.

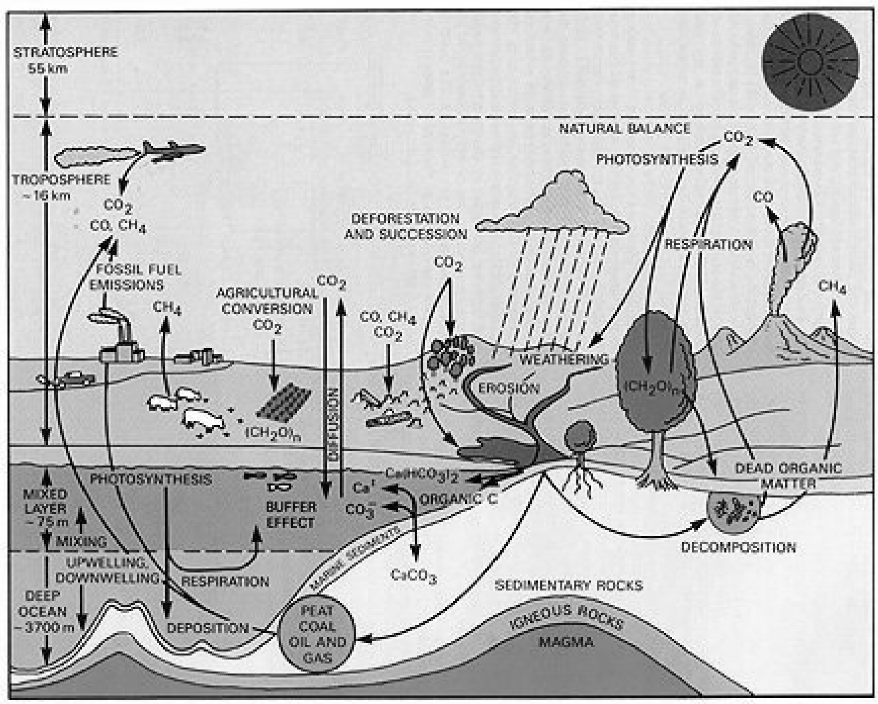


Figure 1: The Carbon Cycle (Short, 2004)**.** The sun initiates the carbon cycle through plant photosynthesis. Some plants are eaten by animals. Animals and other plants then decay into fossil fuels that are harvested for their energy capacity.

Unfortunately, fossil energy formations take significant time to develop (Grassroots Marketing Alliance, 2003a). Alarmingly, humans are consuming the products of the sun faster than the rate at which they are replenished through these natural processes (Tucson Electric Power, ND). To curb the imminent depletion of these energy resources, man must choose one of two paths: either reduce consumption of fossil energy to a rate less than that of natural production or bypass the fossil fuel creation process altogether. The former appears infeasible given current technology, consumption, and consumer

attitudes; the latter is a reality today with solar energy technology systems including photovoltaics.

1.1.2. Energy Source Capacity

Estimates of earth's usable solar energy gain vary. According to the United States Department of Energy (USDOE), enough sunlight reaches the earth each minute to meet global energy requirements for an entire year (USDOE Office of Energy Efficiency and Renewable Energy (EERE), 2004b). Researchers reported at the Third World Conference on Photovoltaic Energy Conversion that the average square meter of earth's surface receives the energy-equivalent of a full barrel of crude oil (1700 kWh) every year (Kasahara and Plastow, 2003). Further, solar energy is expected to be available for another 4.5 billion years (Grassroots Marketing Alliance, 2003b; Kasahara and Plastow, 2003), whereas, projections of fossil fuel (including oil, natural gas, and coal) availability vary by report origin but often are mere decades. Research by the independent petroleum geologist, Jean Laherrere, shows that the peak productions of oil, natural gas, and coal will occur around 2015, 2030, and 2050, respectively (Laherrere, 2005). The exact figures are not important. The clear conclusion is that fossil fuel sources are finite while solar capacity is, in essence, infinite.

1.1.3. Federal Government Interest

The Clinton administration recognized the sun's bountiful energy as a major renewable resource and, in 1997, unveiled the "Million Solar Roofs Initiative" before a United Nations session on the environment and development. The aim of this initiative was threefold: to reduce greenhouse gas emissions by increasing energy produced from renewable sources, to create tens of thousands of high-tech jobs in the solar industry, and

to encourage the development of a domestic market for solar technologies (Herig, 1999). To this end, the initiative directed the USDOE to lead an effort to put one million solar systems on the roofs of homes and other buildings by 2010. The initiative classifies solar systems into two basic types: photovoltaic systems and solar thermal systems (Herig, 1999).

In 1999, the Clinton administration again reiterated its interest in renewable energy with the release of Executive Order (EO) 13123, "Greening the Government through Efficient Energy Management," which required federal agencies to reduce greenhouse gas emissions and expand their use of renewable energy. Additionally, the order expanded the Million Solar Roofs Initiative by directing federal government agencies to endeavor to install 20,000 solar systems on federal facilities by 2010 (Clinton, 1999).

More recently, the Bush administration's fiscal year 2003 budget proposed $4.6 billion to be spent over five years to encourage the use of residential solar energy systems and commercial investments in various renewable energy sources including solar (White House Web Site, 2002). Then, in 2004, USDOE EERE published the *Solar Energy Technologies Program: Multi-Year Technical Plan*, which describes the "rationale, approaches, and results" expected on the path to making solar energy a viable and attractive renewable energy source. The report covers 2003 though 2007 "and beyond" (USDOE EERE, 2004d). Further, the Energy Policy Act of 2005 temporarily raised business tax credits for the purchase and installation of photovoltaic and other renewable source systems from 10% to 30% and included for the first time since 1985 a temporary federal tax credit (also 30%) for the purchase and installation of residential systems (Solar Energy Industries Association, 2005). Finally, the Million Solar Roofs Initiative

was replaced in 2006 by a new program called "Solar Powers America" (USDOE EERE, 2005) Clearly, the potential of solar energy is viewed not only as a necessary step in the development of national energy and environmental goals, but it is also carries significant political interest.

1.1.4. Photovoltaic Effect

A monocrystalline silicon photovoltaic cell (Figure 2) is the simplest configuration and the best to demonstrate the photoelectric effect. This cell is made of two layers of the light-absorbing, semiconductive material (Davidson, 2004; USDOE EERE, 2004c). Different impurities have been added to each layer (a process called "doping") to give the layers special properties. The top layer has an excess of electrons (the n-doped layer or n-silicon), while the bottom layer has an excess of missing electrons or "holes" (the p-doped layer or p-silicon). When the two layers are formed, the excess electrons of the n-doped layer shift to the p-doped layer to create electrical equilibrium in a fixed field. When a photon of light enters the cell's upper, n-doped region, the energy bumps an electron from its atom. The electron moves randomly until it finds a hole to fill. Electrons near the layer boundary (p-n junction) may be drawn across the boundary due to the electrical field, but they cannot return against the field gradient, resulting in an imbalance of charge. To resolve the non-neutrality, an electron must return to the top layer through any available conductive path. This return is tapped as direct current (DC) electricity (Davidson, 2004; USDOE EERE, 2004c).

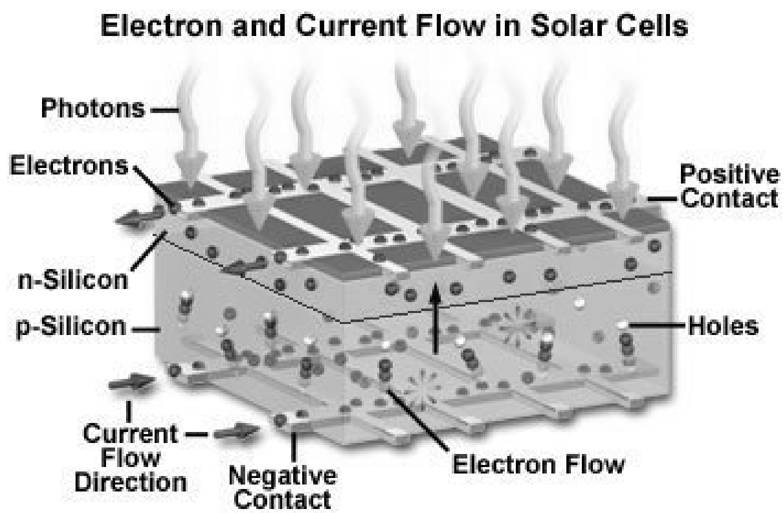


Figure 2: The Photoelectric Effect (Davidson, 2004) (used by special permission). A photon enters the top of a bi-layered, doped cell and knocks an electron from its atom. The electron crosses from the upper layer to the lower layer creating a charge imbalance. The imbalance is resolved, and electricity is generated, when an electron returns to the top layer through a conductive medium.

1.2. Problem Identification

The US Air Force is obligated to comply with all current EOs and, as such, must comply with EO 13123. Although the language of EO 13123 related to solar technologies is not directive in nature, the intent is clear: all federal agencies must attempt to increase their use of renewable energy (Clinton, 1999).

Previous research at the Air Force Institute of Technology developed a model to help determine generally which renewable source (wind, solar, or geothermal) is the best option for a particular base (Duke, 2004). This research assumes that the choice is solar electric and now aims to determine what types of specific systems are the best options. Photovoltaic technologies may be considered either during the design process, typically called building-integrated photovoltaics (BIPV), or by applying the solar technologies to existing infrastructure. Although BIPV solar systems may be less expensive and more

efficient overall (Kiss and Kinkead, 1995), the time horizon to realizing these savings and efficiencies is long, due to extensive funding, design, and construction processes. Alternatively, the Air Force has thousands of acres of undeveloped land and thousands of existing facilities. Placing photovoltaic systems in this unused land space and on existing structures' roofs could meet the objectives of EO 13123 much sooner.

Given the multitude of placement options, the variety of photovoltaic choices, and the differing needs of Air Force bases, a decision maker's task of choosing the appropriate technology is very complex. So, how does a local decision maker make the choice between various systems? What tools are available to the decision maker?

1.3. Research Objective and Research Questions

Currently, there exists no objective process that employs a decision maker's value system to quantify the advantages and disadvantages of installing photovoltaic systems. This research aims to fill that gap by providing a repeatable and objective, value-focused model to assist Air Force decision makers when evaluating photovoltaic options for buildings and sites at bases in the continental US. Research questions that will be addressed include the following:

1. What are Air Force decision makers' objectives with respect to sources of electrical energy, and how does the decision maker value various aspects and qualities of photovoltaic technologies?

2. How do retrofitted applications of photovoltaics perform in various regions of the country?

3. How have multiple-objective decision models been used previously in the selection of energy sources?

4. What are the life cycle environmental burdens of photovoltaics?

1.4. Research Approach

The primary purpose of this research is to develop a multiple-objective decision analysis model to quantify a decision maker's objectives related to selecting, installing, and operating photovoltaic systems. Value-Focused Thinking (VFT) is a decision modeling technique that centers on a decision maker's value system. By concentrating on values rather than alternatives, the door is opened to vast opportunities for creative problem solving. A decision maker may realize potential alternatives not previously considered. Moreover, the door may be opened further to alternatives previously deemed impractical given concrete objectives, yet now considered feasible given a broader and more abstract set of objectives.

The process for developing a VFT model requires one or more elicitation interviews with the decision maker. Based on these interviews, the researcher will determine the decision maker's weightings of attributes as well as mathematical approximations of evaluation measure functions. Once the alternatives are scored and rank-ordered, the decision maker will have a quantified, objective list to make his or her final determination. The first two research question will be answered by developing a VFT model. The remaining two research questions will be addressed with a thorough review of the current literature.

1.5. Significance

The greatest benefit of this research will be the creation of a model for quantifying a decision maker's objectives. This quantification will lead to the objective ordering of alternatives from which the decision maker may select the most appropriate photovoltaic system. Although this model will be created based on only a few Air Force decision

makers, its power and fundamental value will come from extending applicability to local decision makers across the Air Force. Each local decision maker will be able to insert his or her own value structure to develop an ordered, objective list of the alternatives available to him or her.

1.6. Research Assumptions

Value-Focused Thinking is a powerful tool; yet, like any modeling technique, several assumptions must first be expressed. First, this model assumes that base leadership is open to the concept of photovoltaic electricity generation. Without the leadership's buy in, no project will ever get out of the planning stage. Second, the model assumes local utility companies and the political environment support installing PV on the base. Any amount of electricity that the base produces on its own is electricity no longer purchased from the utility. This could have a profound effect on the utility's profits. Third, as with any constructed system, the final solar product is only as good as the materials and installation methods used to put it in place and the maintenance plan that keeps it running. This model assumes all solar systems are running at expected design efficiency. Minor maintenance must be performed to keep the systems running at peak performance (such as keeping the collectors clean (Pearsall and Hill, 2001)). Further, calculations involving electrical output are based upon an average year's solar radiation. Annual fluctuations should be expected. Fourth, this model considers only grid-connected systems. Therefore, the additional technology and maintenance expense for energy storage necessary for off-grid systems is not considered. Fifth, the model was constructed around the value system of only a handful of decision makers. It is fair to say that the model could be used by any decision maker, but it may require minor

adjustments to make a perfect fit for individual objectives. Finally, the aesthetic component of any photovoltaic system is highly subjective and largely variable among the population. It assumed that aesthetics are not an important factor since it is too difficult to please everyone.

1.7. Summary

Fossil fuels are currently being consumed faster than they can be replaced. Our nation's leaders recognize that energy diversification with renewable sources is key to maintaining our economy and the environment; thus, they have directed federal agencies to strive to increase the use of renewable energy. Photovoltaic technologies are one piece of the renewable energy pie. Although a major strategy should be the integrated design of photovoltaics on new construction projects, a significant consideration should be the installation of photovoltaic systems onto existing structures. This research will develop a model to quantify and rank various photovoltaic technologies versus the *status quo* to determine what alternatives will most align with Air Force energy objectives. The model will ultimately be applicable at any decision making level and will enable the Air Force to comply with directives.

2. Literature Review

2.1. Introduction

In this chapter, the reader is presented with several background and literature topics. First, the chapter introduces the relevant federal mandates, including Executive Order (EO) 13123, as well as applicable Department of Defense (DoD) and Air Force guidance. These are the primary motivators for the research. Then, since the research objective is to develop a decision model, the chapter will focus on methodological matters, including a brief summary of several model types and a thorough discussion of the model of choice, Value-Focused Thinking. Finally the chapter will end with a description of photovoltaic technologies, including their development, employment, and environmental aspects.

2.2. Federal Mandates and Agency Guidance

2.2.1. Federal Mandates

Energy legislation has been around for some time, but the first law directing federal agencies to take steps to improve energy management was the National Energy Conservation Policy Act (NECPA) of 1978 (NECPA, 1978). This law was written into US Code in Title 42, Chapter 91. Since the law was introduced in response to the then recent oil crisis, the government was searching for ways to both reduce reliance on foreign energy supplies and increase the availability of domestic renewable energy sources. As such, the law introduced a provision entitled *Federal Photovoltaic Utilization*, in which the federal government created a commercialization program "for the accelerated procurement and installation of photovoltaic solar electric systems"

(NECPA, 1978) at federal facilities. The program had four main objectives: first, to increase general access to photovoltaic technologies by speeding the growth of the domestic photovoltaic industry; second, to reduce fossil fuel costs to the federal government; third, to promote federal use of methods that would reduce lifecycle costs to the government; and fourth, to collect performance data on the commercialization program. To this end, the law authorized the appropriation of $98,000,000 between fiscal years 1979 and 1981 (NECPA, 1978).

Two decades later, EO 13123, "Greening the Government through Efficient Energy Management," was signed by President Clinton in 1999 (Clinton, 1999). In EO 13123, the federal government recognized that, as the nation's largest energy consumer, it can make a significant impact on the environment by improving its energy management. Likewise, with the federal government's colossal annual energy expenditures, it has an immense ability to promote energy efficiency and the use of renewable energy technologies. Related to this research, EO 13123 implemented three policies that have far-reaching effects. First, EO 13123 enhanced the Million Solar Roofs Initiative by directing that federal government agencies seek to install 2,000 solar roofs facilities by the year 2000, and 20,000 solar roofs by 2010. Second, EO 13123 directed the Secretary of Energy to establish goals that led agencies to increase their consumption of energy from renewable sources as a percentage of overall consumption (Clinton, 1999). In 2000, the secretary set this goal at 2.5 percent of total energy consumed. The target date was the end of 2005 (USDOE EERE, 2000). As of March, 2004, the renewable usage rate was 1.93 percent, or about 77 percent of the 2005 goal (USDOE EERE, 2004a). The

DoD met the target by the end of 2004 (U.S. DoD, 2005a). Third, EO 13123 leaves open the door for agencies to reap return on their investment. The EO states that agencies with

> “statutory authority to retain a portion of savings generated from efficient energy and water management are encouraged to permit the retention of the savings at the facility or site where the savings occur to provide greater incentive for that facility and its site managers to undertake more energy management initiatives, invest in renewable energy systems, and purchase electricity from renewable energy sources” (Clinton, 1999).

Unfortunately, the DoD is not such an agency, but it is interesting to note the possibility for realized savings should the statute change favorably.

Referring back to the first paragraph of this section, NECPA was amended by the Energy Policy Act of 1992 but without changes significant to this research (EPAct, 1992). However, the Energy Policy Act of 1992 was later amended by the Energy Policy Act of 2005, signed by President Bush in August of 2005 (Energy Policy Act, 2005). The 2005 Act extended the renewable energy goals originally directed by EO 13123 and established by the Secretary of Energy. The new goals are 3 percent by fiscal year 2007, 5 percent by fiscal year 2010, and 7.5 percent by fiscal year 2013 (Energy Policy Act, 2005).

In his January, 2006, State of the Union address, President Bush introduced the USDOE’s new clean energy initiative called the Advanced Energy Initiative (Bush, 2006). He also spoke of “the need to change how we power our homes and offices.” Further, he declared the federal government “will invest more in … revolutionary solar and wind technologies” (Bush, 2006). To this end, EERE launched the President’s Solar America Initiative (SAI) to fund development toward better performance, reliability, and cost competitiveness of solar systems (USDOE EERE, 2006). As such, EERE’s 2007 budget request reflects a 133% increase over the 2006 appropriation toward photovoltaic

energy system development. Additionally, the Million Solar Roofs Initiative will be replaced in early 2006 by a new program, called Solar Powers America, which will work to deploy technologies developed or improved under SAI (USDOE EERE, 2006). Solar Powers America is intended as a continuation of the Million Solar Roofs Initiative while employing a new approach (USDOE EERE, 2005). Whereas the Million Solar Roofs Initiative was geared toward demonstration, Solar Powers America is expected to involve greater application of innovative approaches to solar energy (USDOE EERE, 2005). Clearly, renewable energy will eventually be a significant part of the nation's energy portfolio.

2.2.2. Department of Defense Guidance

In Senate Report 107-68, Congress directed that the DoD examine and identify where renewable energy use can be implemented at or near military installations (U.S. DoD, 2005a). In response to this request, the DoD drafted the *DoD Renewable Energy Assessment, Final Report* in 2005. Subsequently, in Senate Appropriations Committee Report 108-309, the DoD was again tasked with developing a plan, but this time, to implement the findings of the previous report (U.S. DoD, 2005b). In this latter report, the DoD stated that the "DoD intends to pursue a strategy that carefully considers a combination of both on-installation renewable energy projects and commercial renewable energy purchases based on an analysis of the lifecycle costs, benefits, and source reliability" (U.S. DoD, 2005b). The report also contains an implementation timeline, in which the DoD states that it plans to begin on-installation photovoltaic projects in 2005. Though the report does not specify what specific technologies the DoD plans to implement, it provides a generation range of 0.3 to 0.5 Megawatts. This indicates an

expected system cost that would be in the Military Construction range (those new construction projects which are estimated to cost more than $750,000). The DoD expects to “expand” the installation of solar systems in 2006 and hold the number of new systems constant thereafter (U.S. DoD, 2005b). As of 2005, the Air Force has installed more than 600 kW of photovoltaic capacity at eight facilities and has four additional systems planned (Ringenberg, 2005).

2.2.3. Air Force Policy

In 2001, Major General Robbins, the Air Force Civil Engineer, signed a policy letter on sustainable development. Though the clear intent was to direct the implementation of sustainable facility design, in attachment 1 to the policy he writes, “Renewable energy technologies should be used in facility projects whenever feasible and cost effective. New facilities should meet or exceed current Air Force energy performance goals” (Robbins, 2001). Additionally, he references the United States Green Building Council’s “Leadership in Energy and Environmental Design (LEED™)” Green Building Rating System as the Air Force’s “preferred self-assessment metric” (Robbins, 2001) for sustainable facility design, construction, and modernization. The LEED™ system gives points toward certification based on the implementation of green products, technologies, and approaches in facilities. These include photovoltaic systems (U.S. Green Building Council, 2002).

2.3. Decision Models

Next, the discussion turns to decision models. The decision sciences include several tools for evaluating complex choices in which several competing objectives must be addressed simultaneously. Collectively, these tools are called Multiple Criteria

Decision Analysis (MCDA) models. Each MCDA model has its strengths and special uses. Often, the model type chosen has much to do with the user's familiarity and experience with a particular modeling technique. Most MCDA approaches can be classified as alternative-focused since they employ techniques to determine which alternative of a given set of choices is the most appropriate.

2.3.1. Alternative-Focused Methods

2.3.1.1. Analytic Hierarchy Process

The Analytic Hierarchy Process is a highly structured modeling tool in which objectives and alternatives are organized into a hierarchy. The first tier of each hierarchy branch represents a different, weighted objective. Subsequent tiers may represent a breakdown of their first-tier objectives. The final tier of each branch of the hierarchy represents the scores of the available alternatives with respect to the objective under consideration. All objective weightings and each alternative's objective score may be determined through pairwise comparisons. Finally, each alternative receives a total score by summing the product of the objective weightings and each alternative's objective score (Haas and Meixner, ND).

2.3.1.2. Goal Programming

Goal Programming is very similar to linear programming. In Goal Programming, each objective, or goal, is formulated as a linear constraint. The optimal solution is one that minimizes the total of the weighted, absolute deviations from the objectives (India Infoline Ltd., 2002).

2.3.1.3. ELECTRE

ELECTRE (from ELimination Et Choix Traduisant la Realité (David, ND)) is a general name encompassing five different, but related, modeling techniques (Buchanan et al., 1999). Though the application of the techniques is different, they share a common theory: a focus on thresholds and outranking. Thresholds are defined by levels of a particular alternative criterion beyond which the decision maker is indifferent. Outranking is used by directly comparing one alternative to another to identify an appreciable preference. If a majority of criteria for one alternative are better than the criteria of another alternative, then the former outranks the latter (Buchanan et al., 1999).

2.3.2. Value-Focused Thinking

Each of the previous models is used to rank-order alternatives given a set of objectives. However, the previous models also suffer from another common characteristic; namely, they all focus directly on the available alternatives. The entire analytical process is limited by the alternatives that the decision maker has deemed are available or most important. These models may be called Alternative-Focused Thinking (AFT) models. Because of their methodology, the unforeseen late addition of a new alternative causes the entire model to break down. Keeney notes that alternatives are only important because they are the “means to achieve values” (Keeney, 1996). Therefore, the values themselves are more important rather than the alternatives (Keeney, 1996).

Keeney developed the decision modeling technique known as Value-Focused Thinking (VFT) in response to the lack of value-focused approaches in the decision sciences. Contrary to alternative-focused methods, VFT seeks first to identify the

important objectives and characteristics surrounding a decision and quantify them (Keeney, 1992; Tangen, 1997). Keeney also makes the assertion that a decision problem need not carry a negative connotation. Rather than referring to decision *problems* in which a decision maker must solve the problem by choosing among available alternatives, decision makers should refer to decision *opportunities* (Keeney, 1992). Each decision is an opportunity to create new alternatives (Keeney, 1992). Since VFT is the chosen modeling technique used in this research, a more detailed discussion is included.

2.3.2.1. Fundamental Objectives and Means Objectives

In any decision context, the first step toward a solution is making a list of one's objectives. Simply making the list, however, is only part of the process. Objectives may have one of two purposes based on their contextual use (Keeney, 1996). The objective or objectives that consider the ends that a decision maker values are called fundamental objectives (Kirkwood, 1997). A fundamental object is the reason that there is any interest in the decision at all (Keeney, 1992).

Objectives that ultimately yield the fundamental objective are called the means objectives (Keeney et al., 1996; Kirkwood, 1997). These objectives are not themselves responsible for leading to a solution to the problem, but by following means objectives toward ultimate goals, or ends objectives, a single fundamental objective may emerge for the specific decision (Keeney, 1996).

To tell if an objective is a fundamental objective or a means objective, Keeney applies a simple test he calls WITI or Why Is That Important (Keeney, 1996). When asking this question about an objective, the answer will either be that the objective is a

primary reason for interest in the problem or that the objective is important due to its implications for another objective. In the case of the former answer, the objective is fundamental; if the latter answer is revealed, the objective is the means to an end (Keeney, 1996).

2.3.2.2. Two Approaches to the Value Hierarchy

VFT problems may be approached from either of two opposite paths (Keeney, 1992; Kirkwood, 1997). The bottom-up approach is used when a set of alternatives to a decision is already given. An examination of the alternatives will reveal the attributes for which the alternatives are different. Thus, these attributes may serve as the evaluation measures by which the alternatives are quantified and compared. By grouping related evaluation measures, the modeler may discover hidden objectives important to the decision (Keeney, 1992; Kirkwood, 1997).

The top-down approach, used when alternatives are not available or clearly defined, is the favored approach (Keeney, 1992; Kirkwood, 1997). This approach uses the fundamental objective as the starting point and divides it into smaller and smaller objectives in successive tiers until the decision problem has been thoroughly dissected into its most basic, measurable elements. The top-down approach thus focuses attention only on what is important to the decision maker, objectives and the fundamental decision, and is the better method for developing alternatives (Keeney, 1992; Kirkwood, 1997).

2.3.2.3. Value Hierarchy Properties

A value hierarchy is shown in Figure 3. The hierarchy is constructed of tiers and branches. Tiers represent evaluation considerations that are the same distance from the fundamental objective (Kirkwood, 1997). Each successive tier further from the top

contains more detail about the fundamental decision. Evaluation considerations in the same tier are weighted against each other during analysis (Kirkwood, 1997). Groups of related evaluation considerations are clustered in branches.

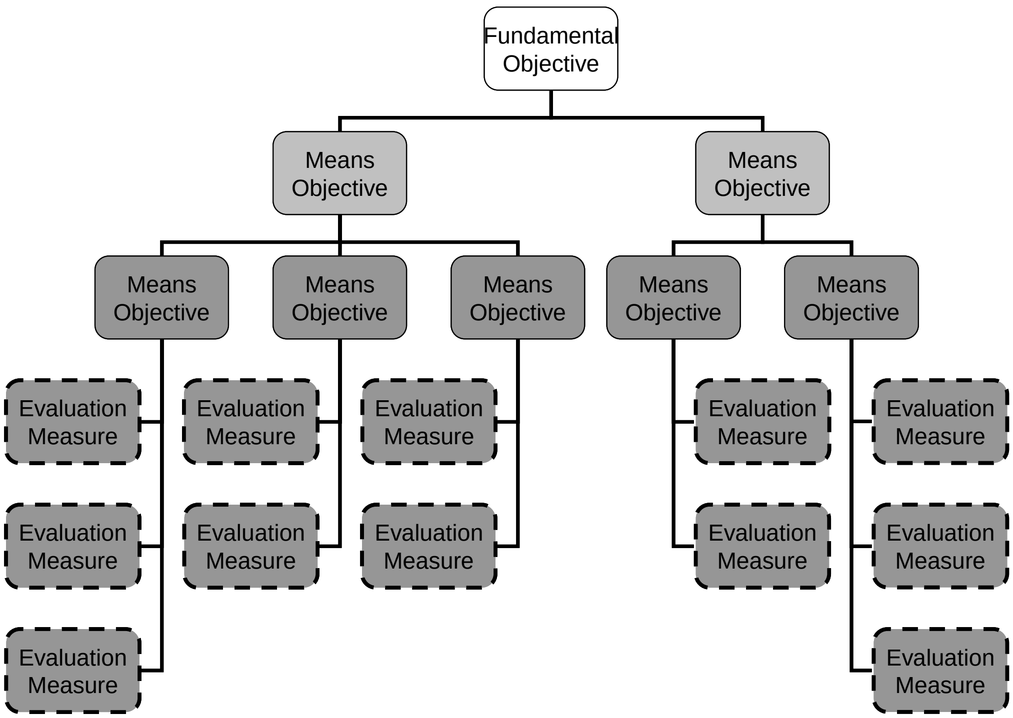


Figure 3: A Value Hierarchy. A Value Hierarchy is constructed of tiers and branches. Tiers are evaluation considerations that are equidistant from the fundamental objective. Branches are groups of related evaluation measures (Kirkwood, 1997).

Since values themselves are abstract concepts that often cannot be directly measured, a combination of quantitative and qualitative evaluation measures (also called measures of effectiveness, attributes, or metrics (Kirkwood, 1997)) are established. These evaluation measures permit clear scoring of alternatives for each objective (Kirkwood, 1997). Each evaluation measure is tied to a single-dimensional value function (SDVF) which converts a raw, dimensional score into a dimensionless value between zero and one, where zero represents the least desirable condition and one

represents the most desirable condition. Evaluation measures may fit into one of the classifications depicted in Table 1. Natural scales have a common interpretation by everyone. Constructed scales have been developed to measure the degree of achievement of a particular objective in a specific decision problem or where a natural scale is not appropriate or does not exist. Direct scales measure the degree of achievement of an objective directly, while proxy scales measure the degree of achievement for a related objective (Kirkwood, 1997).

Table 1: Examples of Evaluation Measure Scale Types (Kirkwood, 1997)

	Natural	Constructed
Direct	Profit in Dollars	Pictures of Visual Haze for SO_2 Concentration
Proxy	Temperature in Kelvin for Thermal Energy*	Gross National Product for Economic Well-Being

* Not from the cited reference.

Unweighted evaluation measures individually only provide a piece of the overall value for any given alternative. In order to carry meaning, all the evaluation measures of a particular alternative must be weighted and added together. It is this weighted sum of all evaluation measures, called the multiobjective value function or additive value function that determines an alternative's final value. The multiobjective value function is simply a mathematical representation of the weighted value hierarchy and is shown in Equation 1 (Kirkwood, 1997).

$$v(X_1, X_2, X_3,\ldots, X_i) = w_1 v_1(X_1) + w_2 v_2(X_2) + w_3 v_3(X_3) + \ldots + w_i v_i(X_i) \tag{1}$$

where

$v(X_1, X_2, X_3,\ldots, X_i)$ is a particular alternative's value for its given scores,
$X_1, X_2, X_3,\ldots, X_i$ are evaluation measures,
$v_i(X_i)$ is the SDVF of the measure, X_i, and
w_i is the weighting assigned to $v_i(X_i)$.

By ranking the valued alternatives, in which higher values are better, the best alternative can be revealed to the decision maker (Kirkwood, 1997).

A hypothetical alternative with a final value of 1.00 indicates that all measures were satisfied to the greatest degree (Kirkwood, 1997). Conversely, another hypothetical alternative with a final value of zero achieves, at maximum, the least preferred value for all measures. A third hypothetical alternative whose final value is 0.78 can be described as being 78 percent of the distance "in a value sense" (Kirkwood, 1997) between the hypothetical worst alternative and the hypothetical best alternative. However, without a discussion of the ranges of each evaluation measure, the final values of alternatives cannot be described in relative terms. The values only illustrate the relative rank order of alternatives. In other words, an alternative with a final value of 0.90 is not twice as good as an alternative with a final value of 0.45 (Kirkwood, 1997).

2.3.2.4. Value Function Assumptions and Characteristics

In order for the multiobjective value function (and, by default, the value hierarchy) to be valid, Kirkwood specifies several assumptions that must first be met, including mutual exclusivity and collective exhaustiveness, independence, operability, and small

size (Kirkwood, 1997). Further, VFT models typically exhibit the three characteristics of objectivity, defensibility, and repeatability (Weir, 2005).

2.3.2.4.1. Mutual Exclusivity and Collective Exhaustiveness

Mutual exclusivity, or non-redundancy, means that no two measurement considerations at any position in the value hierarchy intersect. Kirkwood clarifies that the definition of a hierarchy implies mutual exclusivity since each level of a hierarchy is a division of the higher level (Kirkwood, 1997). Further, if two measures are redundant, then summing their weighted values to determine the final alternative value will result in an inadvertent "double-count" of that particular attribute and will ultimately give more weight to the attribute than intended (Kirkwood, 1997).

Collective exhaustiveness indicates that all measures throughout the hierarchy collectively encompass the necessary attributes important to the fundamental objective (Kirkwood, 1997). If any relevant measure is omitted, then the analysis may not be able to accurately discriminate between two alternatives that are truly preferentially different (Kirkwood, 1997).

2.3.2.4.2. Independence

The evaluation measures of the hierarchy must also be independent of each other. Independence implies that no two measures in the hierarchy are affected by each other. Kirkwood gives the example of an evaluation consideration that might be applied when searching for a job (Kirkwood, 1997). He calls it "economic issues," and its measures include "salary," "pension benefits," and "medical coverage." The values of these measures to a job-seeker change depending on their corresponding levels. For example, if a particular job offering includes a greater medical coverage plan, then the value of

“salary” may be reduced. Similarly, if the job offer includes a larger salary, then, perhaps, the importance of “pension benefits” decreases since the job-seeker may be better able to invest for retirement out of his direct earnings. Interdependence among measures makes comparison of alternatives more difficult (Kirkwood, 1997).

2.3.2.4.3. Operability

Operability refers to the terms used in the value hierarchy (Kirkwood, 1997). The terms must make sense to the intended audience. Scientists and analysts may describe attributes in very technical and precise terms, but if the audience includes the general public or a decision maker with a different background, as is often the case in the Air Force, then the terms used to describe the attributes must make sense. Likewise, the measures themselves must be coherent to the audience. Therefore, it may be necessary either to slice up a complex evaluation measure into more understandable measures or to combine several technical measures into a collective measure if either path makes the hierarchy more clear (Kirkwood, 1997).

2.3.2.4.4. Small Size

Generally, a smaller hierarchy is easier to manage and convey (Kirkwood, 1997). A smaller hierarchy will also require less time, effort, and financing to evaluate since every measure must be scored for each alternative. Often hierarchies slowly grow larger as more and more evaluation measures are added to the model. However, Keeney and Raiffa’s Test of Importance is a good tool to eliminate unnecessary measures. This assessment asks if the alternatives are appreciably different with respect to the measure and includes the measure only if the variation changes the preferred alternative (Kirkwood, 1997).

2.3.2.4.5. Objectivity, Defensibility, and Repeatability

Three characteristics often used to describe VFT models are objectivity, defensibility, and repeatability. VFT models are objective because the decision process does not allow a decision maker to favor any particular alternative since what is important, the decision maker's values, are specified up front (Weir, 2005). If, for example, the decision is partly based on color, and the decision maker favors red, then any alternative that is red is scored the same. VFT models are defensible in the sense that every evaluation consideration in the model has been carefully scrutinized (Weir, 2005). Evaluation considerations are chosen only if they represent quantifiable measures that meet all of the above assumptions. Finally, VFT models are repeatable since, once alternatives have been scored, a decision maker will get the same result every time he uses the model unless his weightings change (Weir, 2005).

2.3.2.5. Alternative Focused Thinking versus Value-Focused Thinking

Alternative-focused approaches first look at the available alternatives and try to determine which alternative best meets the objectives. This does not preclude the selection of an undesirable alternative if all the given choices are considered poor (Kirkwood, 1997). Thus, one disadvantage of AFT methods is that the chosen alternative may be merely the least unpleasant of several bad alternatives. A second disadvantage of AFT methods is that their use could lead to the exclusion of better alternatives not yet identified. Attention is devoted solely to the available alternatives and no effort is made to develop new alternatives. Third, a decision maker might unconsciously anchor upon a favorite alternative and judge each remaining alternative against this favorite, or worse, the decision maker could inadvertently develop a model that gives extra weight to the

favorite alternative such that the alternative has a greater probability of a high ranking. Yet another weakness of AFT methods relates to associative reasoning. Associative reasoning permits decision makers to concentrate on factors that appear relevant only because they are the first and easiest that come to mind. Decision makers lose "conscious control" of the decision making process by relating the current decision to a similar past decision. The decision maker then recalls alternatives that worked in the past and fails to consider better, current, and more applicable alternatives. This process is risky since each decision is truly unique, and past decisions' alternatives will not be the same as the alternatives for the current decision. Associative reasoning can be minimized by focusing on the objective and the values associated with the objective (Kirkwood, 1997) which is the basis of VFT.

Since VFT is a whole different way to approach a decision problem, many of the benefits of VFT are simply the converse of the disadvantages of AFT. Perhaps the greatest advantage of VFT is that the technique has the ability to reveal concealed alternatives (Keeney, 1992; Kirkwood, 1997; Tangen, 1997). Keeney states that it is values alone that matter in a decision problem. The alternatives are only important as a means to achieve one's objectives (Keeney, 1996). Thus, by analyzing the value hierarchy, a decision maker focuses his attention on what is important to the decision, not merely what is available in the set of given alternatives. Identifying one's values and applying some amount of creativity lead to the development of new alternatives with more desirable consequences. Other advantages of VFT are represented in Figure 4, taken from Keeney (1994).

Figure 4: The Central Role of VFT and Several Benefits (Keeney, 1994)**.** VFT's central role of "thinking about values" is surrounded by several benefits associated with the technique.

León set out to determine if the structure of objectives generated with VFT was fundamentally different from the structure of objectives generated with AFT methods (León, 1999). In two studies, León used statistical methods to compare the results of VFT and AFT. The first study asked if the structures of objectives made with using the two methods are different. Using 28 students assigned either VFT or AFT in a decision situation, León found that the structures are indeed different: the VFT group yielded a total of 12 objectives in three first-tier objectives (an indication of hierarchy) and nine specific objectives while the AFT group had no hierarchy of note and only five specific objectives. This shows that VFT methods do generate different results from AFT methods. The VFT structure is much larger with more objectives and measures. León postulated that these differences may lead to greater generation of alternatives.

The second study asked if five of the advantages of VFT proposed by Keeney (1992) are actually realized. The five advantages that León specified are listed in Table 2.

Table 2: Five Advantages of VFT (León, 1999)

1. Alternatives with more innovative characteristics are included.
2. The range of alternatives included becomes wider.
3. The future consequences of decisions are taken more into account.
4. Alternatives that at first glance would not be considered are integrated.
5. More desirable consequences are considered.

León asked 30 students to evaluate two objective structures when choosing courses in a curriculum. He found that all five advantages were achieved. Overall, after analyzing both empirical studies, León concluded that VFT is "more complete, more operational, equally concise, and more understandable" when compared to AFT methods (León, 1999).

2.3.3. VFT Decision Modeling

2.3.3.1. Comparison of Alternative-Focused and Value-Focused Methods

As AFT and VFT intend to do the same thing, that is, solve complex problems, naturally, they will have many of the same steps (Keeney, 1992). However, their methodologies differ in the order of their steps and approach that each method takes. Table 3 briefly compares the order of steps involved in alternative-focused and value-focused models.

Table 3: Comparison of Steps in AFT and VFT (Keeney, 1992)

Alternative-Focused Thinking	Value-Focused Thinking
1. Recognize a decision problem	1. Recognize a decision problem
2. Identify alternatives	2. Specify values
3. Specify values	3. Create alternatives
4. Evaluate alternatives	4. Evaluate alternatives
5. Select an alternative	5. Select an alternative

As mentioned above, the steps look nearly identical save for the reversal of steps two and three. Both AFT and VFT begin by first recognizing that there is a problem to be solved. Step two in AFT then leads the analyst to identify all the available alternatives. Depending upon the decision context, the list of alternatives can sometimes be narrow and easy to identify (Keeney, 1992). Even if the analyst attempts to search for additional alternatives, the thought process will likely be stifled due to anchoring on the given alternatives (Keeney, 1992). The third step in AFT encourages the analyst to specify values; however, this usually leads to specifying values related only to the alternatives, not about the greater objectives of the decision problem (Keeney, 1992). Another danger results from favoring a particular alternative such that the values specified will most likely favor the alternative in the scoring process (Kirkwood, 1997; Weir, 2005). The final two steps in the AFT method evaluate the alternatives and select the best alternative. It should be reiterated that the selection from a narrow field of choices is likely merely for the least bad alternative (Kirkwood, 1997).

Step two of VFT differs from that of AFT. In VFT, the second step is to specify one’s values. It is emphasized that values are specified before alternatives are considered (Keeney, 1992). This is the fundamental difference, and strength, of VFT. Values should be fully specified, qualitatively examined, and quantified if possible. Thus, having fully expressed the values, they should be used to create the alternatives, the third step. Now the alternatives can be examined and evaluated based on the specified objectives of the decision problem (Keeney, 1992).

Kirkwood takes a very similar approach to solving decision problems using value-focused methods, though his five-step approach (shown in Table 4) is shifted somewhat from Keeney's sequence. Kirkwood's method combines Keeney's first two steps into one in which objectives and measurement considerations (values) are again specified up front (Kirkwood, 1997). Then, alternatives to meet the objectives are created. The major emphasis is, again, that values come first, then alternatives (Kirkwood, 1997).

Table 4: A Strategic Approach to Decision Making (Kirkwood, 1997)

1. Specify objectives and scales for measuring achievement with respect to these objectives. 2. Develop alternatives that potentially might achieve the objectives. 3. Determine how well each alternative achieves each objective. 4. Consider tradeoffs among the objectives. 5. Select the alternative that, on balance, best achieves the objectives, taking into account uncertainties.

2.3.3.2. The Ten-Step Method

Shoviak derived a 10-step process in part from the works of Keeney and Kirkwood (Shoviak, 2001). These steps break down VFT model development into very discreet and manageable tasks. The sequence is listed in Table 5.

Table 5: 10-Step VFT Process (Shoviak, 2001)

1. Identify the problem and determine the fundamental objective. 2. Develop an objectives hierarchy. 3. Develop evaluation measures. 4. Create the single-dimensional value functions. 5. Weight the objectives hierarchy. 6. Generate alternatives. 7. Score the alternatives. 8. Perform deterministic analysis. 9. Perform sensitivity analysis. 10. Provide overall guidance and recommendations.

Step One, problem and fundamental objective identification, is self explanatory and has been discussed above. Step Two requires the development of a value hierarchy, including arranging all of the non-fundamental objectives. The value hierarchy should feature all of the desirable properties listed above in section 2.3.2.4 above. Step Three is the development of evaluation measures. This step includes determining the limits of the evaluation measures, as knowing the range of the measure is crucial to assigning weights in Step Five. Step Four involves the creation of single-dimensional value functions. Since each evaluation measure has its own scale and dimensional units, the measures cannot simply be added together to determine the overall value of an alternative. Rather, the evaluation measures first must be assigned individual, non-dimensional values ranging between zero and one, where zero corresponds to the decision maker's least desirable value and one corresponds to the most desirable value. The shape of the curve between zero and one is also determined by the decision maker. Since not all objectives carry the same importance to the decision maker, Step Five requires the decision maker to weight the objectives. The decision maker must be fully aware of the ranges of the evaluation measures since the significance of a measure can change depending upon its range. Step Six, creating alternatives, has been discussed previously. Step Seven is to score the alternatives with respect to the evaluation measures. This step can require some time depending on the number and complexity of the evaluation measures. Step Eight encompasses the deterministic analysis; in this case, additive value functions (discussed above) are developed for each alternative. Step Nine is the sensitivity analysis. The weights assigned to objectives in the hierarchy, though carefully elicited, are arguably open to modest variation. A sensitivity analysis of the weights reveals if variation in the

weights has any effect on the final ranking. The weights of objectives are shifted one at a time while the proportionality of the other objectives' weights is held constant. Other model assumptions may also be evaluated for sensitivity to determine their effects on the final ranking. Step Ten, providing the recommendations, logically follows. Having completed the analyses, the findings and recommendations are reported to the decision maker, but since this model is not being developed to solve a particular base's decision problem, Step Ten will not be a part of this research.

This research will follow the 10-step approach. These 10 steps will be further described and implemented in the subsequent chapters of this thesis. Steps One through Six will be covered under Methodology in Chapter 3. Steps Seven through Nine comprise the deterministic and sensitivity analyses of the model. They will appear in Chapter 4. Step Ten will not be presented.

2.3.4. Other VFT Model Used for Selecting Energy Sources

VFT models have been applied in many varying settings. Three models in particular seem to be closely related to this research.

2.3.4.1. Renewable Energy

A VFT model published in 2004 aimed to choose generally which renewable energy source would be the best to provide energy at a given facility (Duke, 2004). The model included three alternatives: solar, wind, and geothermal energy. The author concluded that VFT was a good technique for choosing among the alternatives (Duke, 2004).

2.3.4.2. Renewable Vehicle Fuels

A model published in 2005 was focused on choosing renewable fuels for government vehicles (Queddeng, 2005). This model used two first-tier values, five second-tier values, and 13 third-tier values to fully dissect the decision and evaluate nine alternatives. The author's perspective was focused more on solving the decision problem rather than developing a template model for future users to employ (Queddeng, 2005).

2.3.4.3. Ground-Source Heat Pumps

Another model published in 2005 aimed to evaluate several ground-source heat pump options for military bases (Jeoun, 2005). The model incorporated three first-tier values and five second-tier values to evaluate four alternatives. The author concentrated on developing a template-type model that could be used at any installation rather than focusing on solving a particular base's decision problem. The author concluded that VFT is an appropriate tool for selecting a heating, ventilation, and air conditioning alternative (Jeoun, 2005).

2.4. Photovoltaics

2.4.1. Definitions

2.4.1.1. Photovoltaic Cell, Module, Array, and System

This research will refer to cell, module, array, and photovoltaic system as follows: a cell is the most basic photoelectric generating unit. Several cells connected in a series or parallel circuit make a module. Several modules connected together compose an array. Adding so called "balance of system" (BOS) components such as wiring, support structures, inverters, and electronic switching components rounds out the photovoltaic

system. The following two terms may be used to describe any level of the photovoltaic system.

2.4.1.2. Peak Watts (W_p)

Peak wattage is the DC power rating used to describe the maximum capacity of a given cell, module, or system. Peak watts are measured at 25 ^oC under solar radiation equal to 1 kW/m^2. Average system output in an unspecified "sunny location" may be approximated by dividing peak watts by five (Archer, 2001).

2.4.1.3. Efficiency (η)

Energy efficiency is generally defined as the percent of usable output energy versus the input energy and is calculated as energy output divided by the energy input. Efficiency losses are expected at all levels of the photovoltaic system.

2.4.1.3.1. Cell Efficiency (η_{mp})

Cell efficiency is called maximum-power solar conversion efficiency, η_{mp}. Efficiency is a measure of the cell's ability to convert sunlight to DC electricity. Efficiency is typically given as a percent and is defined by Equation 2 (Bard et al., 1991; Schumacher and Wettling, 2001), where P_{mp} is the maximum power per unit area, or power density (in watts per unit area), and E_o is the incident solar irradiance, or the amount of light from the sun (also in watts per unit area) (Bard et al., 1991; Schumacher and Wettling, 2001).

$$\eta_{mp} = \frac{P_{mp}}{E_o} \qquad (2)$$

2.4.1.3.2. Module Efficiency

The efficiency of photovoltaic modules is less than that of the individual cells that make it up (Pearsall and Hill, 2001). This is partly because individual cell efficiencies are often calculated under laboratory conditions. Commercial modules are exposed to many variables including temperature changes. Increases in temperature often lead to decreases in efficiency (depending on the technology used). Another factor is caused by cell mismatching. No two cells are exactly the same, but, again depending on the technology employed, the least efficient cell dictates the overall module efficiency. A third cause of variance is that efficiency is measured based upon unit area, but in a module, the cells are separated by a few millimeters to prevent short circuiting. This leaves gaps that have no generating capacity. A typical crystalline silicon module is 80 to 90 percent as efficient as the cells that compose it (Pearsall and Hill, 2001).

2.4.1.3.3. System Efficiency

Photovoltaic system efficiency losses occur largely as a result of inverter losses (Pearsall and Hill, 2001). The inverter converts the direct current, as produced by the photovoltaic cells, into alternating current, used by common appliances and electronics, by simulating a sine wave of the necessary frequency (60 Hz in the US). This function is particularly important in grid-connected systems as power received off the grid is in alternating current, and the oscillations of the two power sources must match up. Inverter efficiency is typically greater than 90 percent (Pearsall and Hill, 2001).

2.4.2. History, Development, and Production

2.4.2.1. The Early Days

W. G. Adams and R. E. Day first discovered the photovoltaic effect as early as 1877 by observing voltages in a rod of selenium exposed to light (Archer, 2001). The first publication of the practical application of a photovoltaic device was by Werner von Siemens in 1885 (Archer, 2001), writing of C. E. Fritts' light meter. Siemens wrote that the device demonstrated the first-ever conversion of light into electricity (Siemens, 1885-6). Photovoltaic developments of metal-semiconductor junction devices continued late into the 1930s, but because these devices carried a significant *dark current*, the current caused by innate chemistry rather than light exposure, their measurable photovoltaic response was diminished (Archer, 2001).

2.4.2.2. Crystalline Silicon (c-Si)

The first modern semiconductor-semiconductor junction device was developed by Russell Ohl in 1941, who found that the crystallization of melted silicon returned a significant photovoltaic response (Green, 2001). What he had actually, though unknowingly, demonstrated was a p-n junction formed by the unequal distribution, ironically, of *impurities* as the silicon crystallized (Green, 2001). Silicon has gone on to become the staple of the photovoltaic industry in the form of single- and multi-crystalline cells. Early in development, the feedstock came from the waste of the electronics industry, but more recently, the quantity of photovoltaic cells produced has surpassed this supply such that manufacturers must search for new sources of feedstock (Archer, 2001).

The space age of the 1950s stimulated the growth of the fledgling photoconversion industry (Archer, 2001; Hardingham, 2001; Rau and Schock, 2001). The need for

lightweight and long-lived power sources to run space-based assets such as satellites drove much research into the development and application of photovoltaic devices, but cost savings was not an important consideration. The first terrestrial devices gained popularity in the late 1970s, driven by the rising cost of oil. The 1970s and 1980s also saw the introduction of several alternatives to c-Si-based devices as researchers explored thinner, lighter, and cheaper cells. Of the four main emergent technologies, called thin-films, three contain the heavy metal, cadmium, which potentially negates the positive environmental benefit of photovoltaic energy conversion since cadmium is considered toxic (Archer, 2001). These three are cuprous sulphide-cadmium sulphide, cadmium sulphide-cadmium telluride, and zinc oxide-cadmium sulphide-copper indium diselenide. Bonnet argues that cadmium telluride modules present a negligible risk due to their inherent characteristics (Bonnet, 2001). The fourth thin-film technology is amorphous hydrogenated silicon, also called simply amorphous silicon. Each technology will be briefly discussed below.

2.4.2.3. Cuprous Sulphide-Cadmium Sulphide

Developed in the late 1950s, cuprous sulphide-cadmium sulphide technology was the first thin-film technology to be produced (Archer, 2001). It was particularly attractive because of its simpler manufacturing process. However, the cuprous sulphide layer of the technology was plagued by instability, and it was difficult to establish ohmic contacts (Archer, 2001). Thus, the technology was eventually abandoned in the 1980s as amorphous hydrogenated silicon became the dominant thin-film technology (Archer, 2001; Bonnet, 2001; Rau and Schock, 2001).

2.4.2.4. Cadmium Telluride (CdTe)

Cadmium telluride was first used as a γ-ray detector (Archer, 2001). Although it may, by itself, be doped to form an n-layer and a p-layer homojunction (a photovoltaic cell formed from a dually-doped semiconductor), CdTe performs much better when combined with cadmium sulphide (CdS) in a heterojunction cell (a cell formed by combining two chemically different semiconductors) (Archer, 2001; Bonnet, 2001). Figure 5 shows the cross-section of a typical CdS-CdTe cell, which will henceforth be called by its absorber layer, CdTe. The technology is particularly suited to low costs and moderate efficiencies (Rau and Schock, 2001) and has now been in laboratory development for more than 30 years (Bonnet, 2001). At least two companies are actively developing CdTe modules with efficiencies (as of October, 2005) of 7.3 percent and 10.2 percent (Zweibel, 2005). However, in a major blow to CdTe development, BP Solar, one of the world's largest photovoltaic manufacturers, closed its plants producing CdTe and amorphous silicon (discussed below) without citing specific reasons (Fairley, 2003). An application of CdTe is shown in Figure 6. Perhaps the greatest hurdle to cadmium-based technologies is the toxic nature of one of their main ingredients: the heavy metal, cadmium. Bonnet argues that in the case of CdTe modules, the risk is negligible (Bonnet, 2001). Production involves processes that are well-developed with chemicals that can be managed given current requirements. Laboratory workers have not displayed any unusual uptake of the material. Bonnet even writes that it is "technically and economically possible to design and operate a factory with zero cadmium emissions." Cadmium telluride use is also relatively low risk since the cadmium is strongly bonded to the telluride, yielding an inert compound. Cadmium will only be released above 1000 ^{o}C.

In a fire, the module glass will melt long before these temperatures are reached, and preliminary studies suggest that the CdTe becomes dissolved within the melted glass. Upon reaching the end of their useful life, the modules can be crushed and returned to manufacturers to be recycled into new modules (Bonnet, 2001).

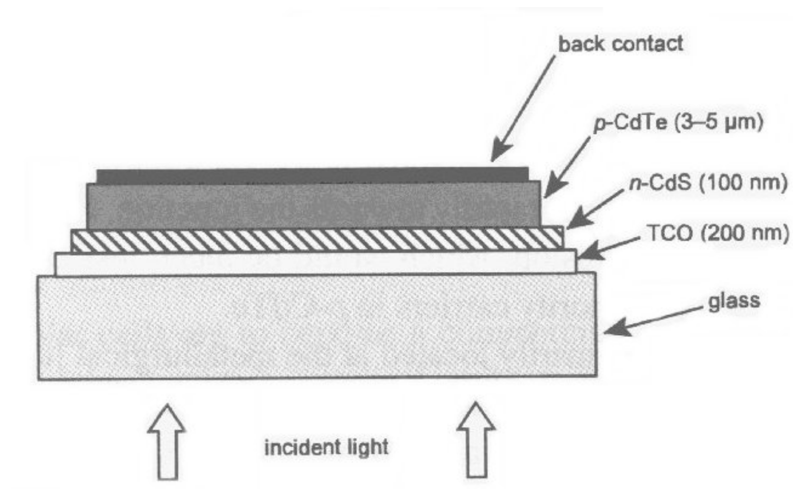


Figure 5: Typical CdTe Cross-Section (Bonnet, 2001). A typical CdTe cell schematic showing the p- and n-layers. In this drawing, the light is entering from below.

Figure 6: An Application of CdTe (Zweibel, 2004). A CdTe field array.

2.4.2.5. Copper Indium Gallium Diselenide ($Cu(In,Ga)Se_2$ or CIGS)

Like CdTe cells, CIGS cells have been around in experimental form for more than 30 years (Rau and Schock, 2001). Similarly, their attractiveness results from relatively high efficiencies with low costs. CIGS cells are actually an alloy of copper indium diselenide and copper gallium diselenide combined with cadmium sulphide and zinc oxide as shown in Figure 7. However, unlike other photovoltaic technologies, and especially those based on silicon semiconductors, these cells have no other technological cousin with which to share the burden of research and development. Much of the advancement in CIGS technology has been forged from a modest knowledge base. Commercial CIGS modules have only been available as recently as 1998, though an elaborate building-integrated application is shown in Figure 8. However, as of 2001, the CIGS cell efficiency record was an astounding 18.8 percent in the laboratory (Rau and Schock, 2001), and, as of October, 2005, modules are reported to achieve efficiencies from 10.2 percent to 13.4 percent (Zweibel, 2005).

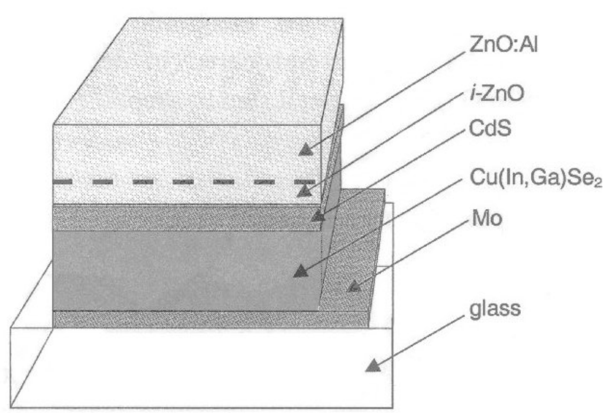


Figure 7: Typical CIGS Cross-Section (Rau and Schock, 2001)**.** A typical CIGS cell schematic showing the three layers above the glass and front contact plate (Mo). In this drawing, the light enters from below.

Figure 8: An Application of CIGS (Zweibel, 2004)**.** CIGS used in a building-integrated form.

2.4.2.6. Amorphous Hydrogenated Silicon (a-Si:H or a-Si)

In the 1980s, the Japanese commercialized a-Si as an alternative to c-Si and developed the industry by creating small photovoltaic panels to power watches and calculators (Archer, 2001; Wronski and Carlson, 2001). Amorphous silicon has several advantages over c-Si. First, several (two or three) cells of varying silicon-based compounds can be stacked on top of each other to absorb a greater range of sunlight wavelengths (Wronski and Carlson, 2001). Second, the p-n junctions of a-Si-based cells tend to be of a higher quality. Third, the manufacturing process uses a lower temperature, about 300 ^{o}C (versus c-Si cells' 500 ^{o}C to 600 ^{o}C and even higher depending on the manufacturing process employed (Green, 2001)). The lower temperature permits greater uniformity of cells deposited over large areas (Wronski and Carlson, 2001) and may also require less energy in production. Unfortunately, a-Si tends also to be less

efficient than c-Si. While the c-Si efficiency record as of 2001 was 24.5% (set in 1998) (Green, 2001), the greatest stable efficiency of a-Si as of 2001 was only 13.0%, though efficiencies greater than 18% have been achieved with crystalline-amorphous silicon hybrids (Wronski and Carlson, 2001). As of October, 2005, module efficiencies ranged between 5.7 percent and a non-independently measured 11.0 percent (Zweibel, 2005). The simplest a-Si cell has a single junction bridging the p- and n-layers. A slightly more complex cell includes an undoped, neutral i-layer (for *intrinsic*). Incorporating the i-layer increases the performance of the cell. Greater efficiencies can be obtained by creating more junctions since a greater spectrum of light is absorbed. Single-junction, tandem-junction, and triple-junction cells are shown in Figure 9. It is important to clarify that a-Si is subject to the Staebler-Wronski effect, in which cells lose 10% to 20% of their efficiency after long-term exposure to sunlight (Archer, 2001; Wronski and Carlson, 2001), though exploiting tandem- and triple-junctions diminish the effect (Wronski and Carlson, 2001). The stabilized efficiency rating given above accounts for this efficiency drop. Amorphous silicon photovoltaics accounted for 12 percent of the photovoltaic market in 2001 (Rau and Schock, 2001) occupying the attention of big-name manufacturers including Sanyo, Canon, and Sharp (although, as mentioned above, BP Solar closed its a-Si and CdTe producing plants in 2003 (Fairley, 2003)). Together, these companies alone planned to manufacture 55 MW_p of capacity in 2001 and 2002 (McNelis, 2001). A roof application of a-Si is shown in Figure 10.

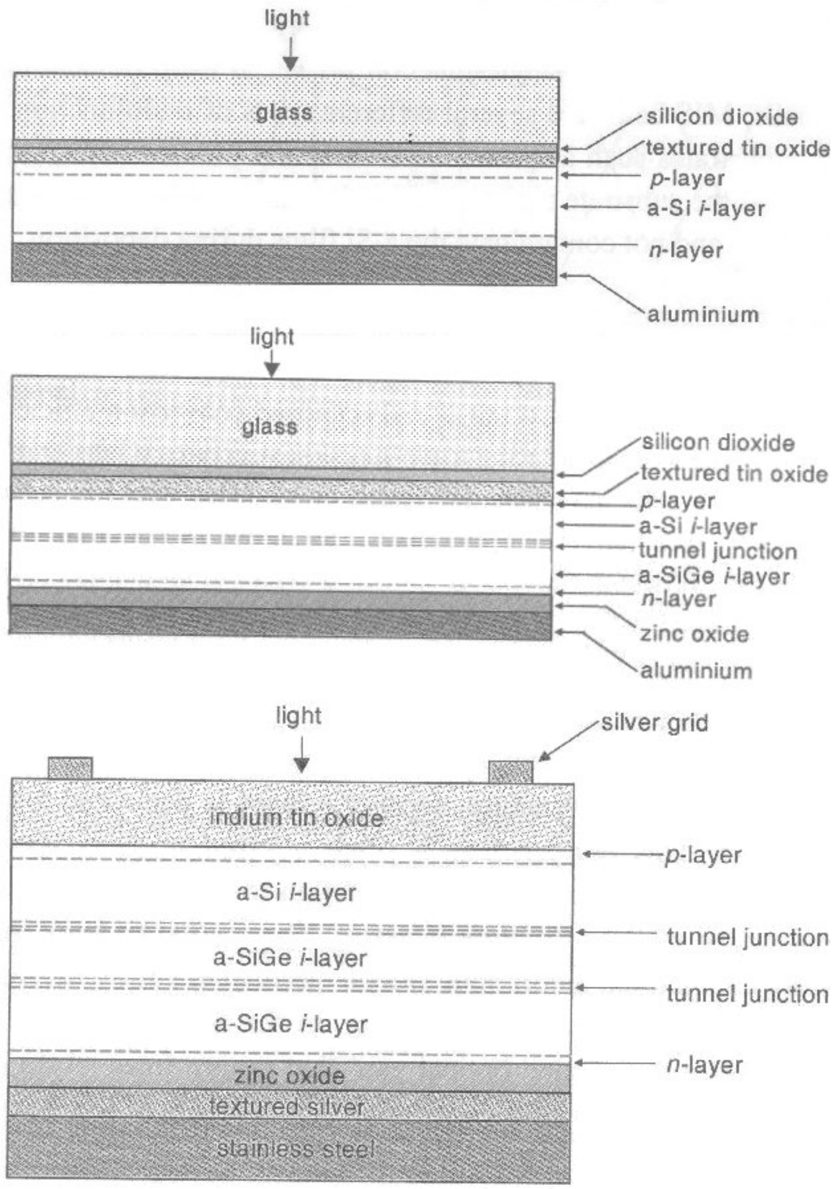


Figure 9: Typical a-Si Cross-Sections (Wronski and Carlson, 2001)**.** Typical a-Si cells showing the p-, i-, and n-layers, as well as contact plates. The top, middle, and bottom schematics represent a single-junction cell, a tandem-junction cell, and a triple-junction cell, respectively. Having more junctions allows the cell to collect a greater spectrum of light and increases efficiency. Notice the light is entering from above.

Figure 10: An Application of a-Si (Zweibel, 2004)**.** A covered parking area decked with a-Si modules.

2.4.3. System Classifications

The above technologies can be developed into several different types of systems, specifically, those that are installed on buildings and those that are installed on the ground. Additionally, the systems may be set up as flat-plate collectors or concentrating collectors. Further, the systems may be fixed, non-moving modules or attached to sun-tracking devices. These are discussed next.

2.4.3.1. Building-Integrated Photovoltaics and Roof-Mounted Photovoltaics

One particularly attractive method of using photovoltaics is to assimilate them right into the constructed building. Called Building-Integrated Photovoltaics (BIPV), these modules actually become essential architectural and structural elements of a facility.

BIPV have several advantages over non-integrated photovoltaics. First, generally where BIPV are used, the requirement for conventional building materials is reduced or eliminated (Kasahara and Plastow, 2003). For example, BIPV include roofing tiles (Figure 11) that replace the need for traditional asphalt shingles while performing comparably (Takenaka et al., 2003). Similarly, modules based on a flexible substrate can be rolled onto a standing seam metal roof and glued in place (Figure 12). BIPV may also include various types of architectural glass. One is a crystalline form that permits light to pass between modules; another is amorphous silicon with a laser-etched back contact that gives the appearance of tinted glass (Kasahara and Plastow, 2003). Perhaps one of the greatest advantages of BIPV is that they consume no land area. Generally, BIPV occupy surfaces for which the conventional use does not change by being clad with photovoltaic modules. BIPV return the land for other uses. Examples of BIPV and roof-mounted photovoltaics are shown in Figure 8 and Figure 10. Residential BIPV systems are often 1 to 5 kW_p (McNelis, 2001), and commercial installations can be in the area of 100 to 1000 kW_p.

Figure 11: Photovoltaic Shingles (Oksolar.com, ND)**.** Photovoltaic shingles (the darker shingles) appear very similar to conventional shingles and perform equally. Installation of photovoltaic shingles actually precludes the use of other roofing materials.

Figure 12: Photovoltaic Rolls (JRCCI Products and Services, ND)**.** Photovoltaic cells on a flexible substrate are delivered in rolls which can be glued between the seams of a standing seem metal roof. This photo shows the backing being peeled off of a flexible roll exposing the adhesive surface.

2.4.3.2. Field Arrays

An example of a field array is shown in Figure 6. An advantage of field arrays is that they may potentially capitalize on economy of scale. The cost of special site construction can be spread over more modules and manufacturers are expected to also provide bulk discounts. However, according to McNelis, decentralized production (not in Megawatt-generating capacities) may actually be more practical (McNelis, 2001). Smaller, distributed systems such as BIPV save on transmission and distribution costs (up to 25 percent per delivered kilowatt-hour), investment costs, and the cost of conventional building materials (McNelis, 2001). Another disadvantage of field arrays is the large footprint that the systems require. In places where real estate is at a premium, field arrays may be cost prohibitive. The example in Figure 6 is a flat plate, fixed tilt array. Field arrays may also be set up as concentrator systems, or they may incorporate solar tracking along one or two axes. These are discussed in the next section.

2.4.3.3. Concentrator Systems and Tracking Systems

Concentrator systems employ optical devices attached to or located near the photovoltaic modules. These optical devices collect and redirect magnified sun light onto the module cells and thereby realize much greater illumination intensity and efficiencies. Concentrating systems typically use either a trough or a dish collector as shown in Figure 13.

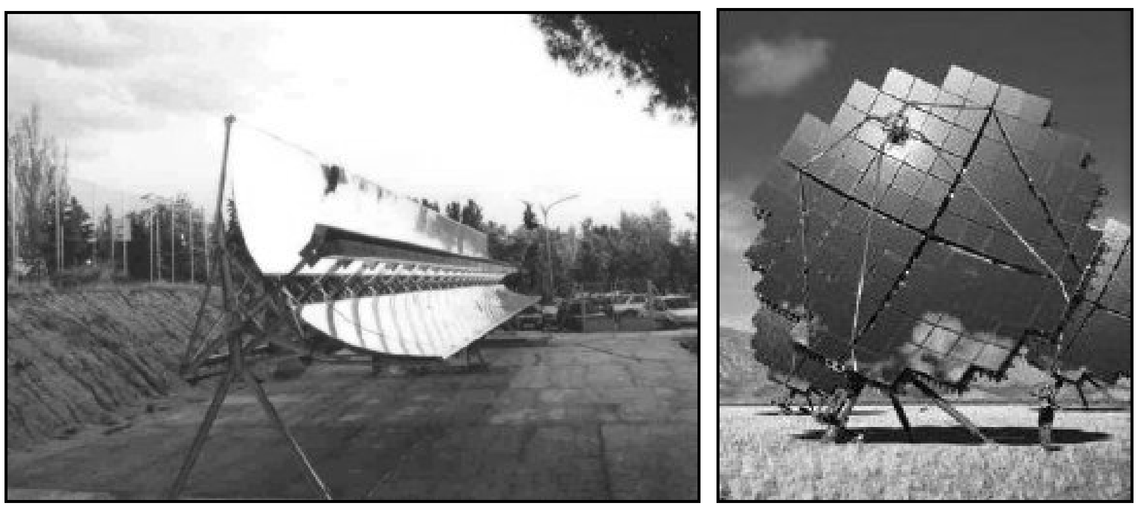


Figure 13: A Trough Concentrator (Lenardic, 2005) **and a Dish Concentrator** (Polytechnical University of Madrid - The Institute of Energía Solar, ND)**.** Two types of concentrating systems are shown. The system on the left is a trough concentrator on the Canary Islands, Spain. The system on the right is a dish concentrator in Australia.

Tracking mechanisms also increase efficiency and output by moving modules to expose them to the sun at an optimized angle. Tracking systems are typically based on one or two axes of rotation as shown in Figure 14.

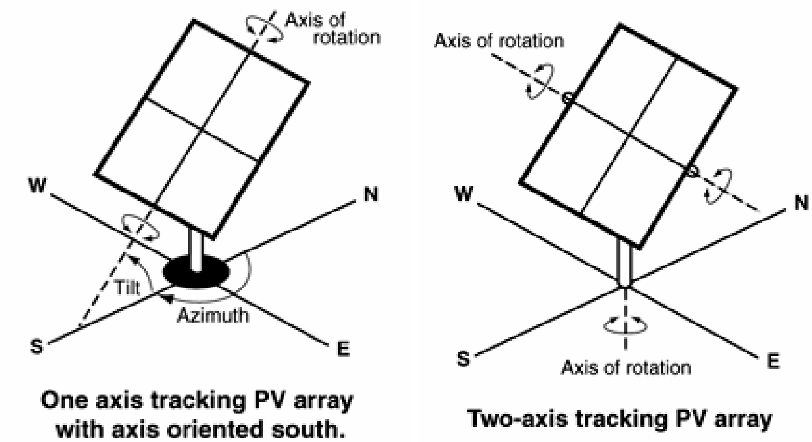


Figure 14: Tracking System Axes of Rotation (USDOE EERE, ND)**.** Tracking systems increase output by exposing the modules to more direct sunlight. The image on the left shows a one-axis tracking system. The system on the right shows a two-axis tracking system.

Systems that include very complex technology or several moving parts naturally will require much more technical expertise to install, operate, and maintain than other systems. Since this research aims to analyze photovoltaic systems for Air Force installations, and it is assumed that Air Force personnel do not commonly possess the technical background to maintain these two types of systems, concentrating systems and tracking systems will not be included in the analysis so further discussion is not warranted.

2.4.3.4. Technology Efficiency Comparison

A comparative history of the efficiencies of major photovoltaic technologies is displayed in Figure 15. This diagram represents the best laboratory efficiencies as of 2005.

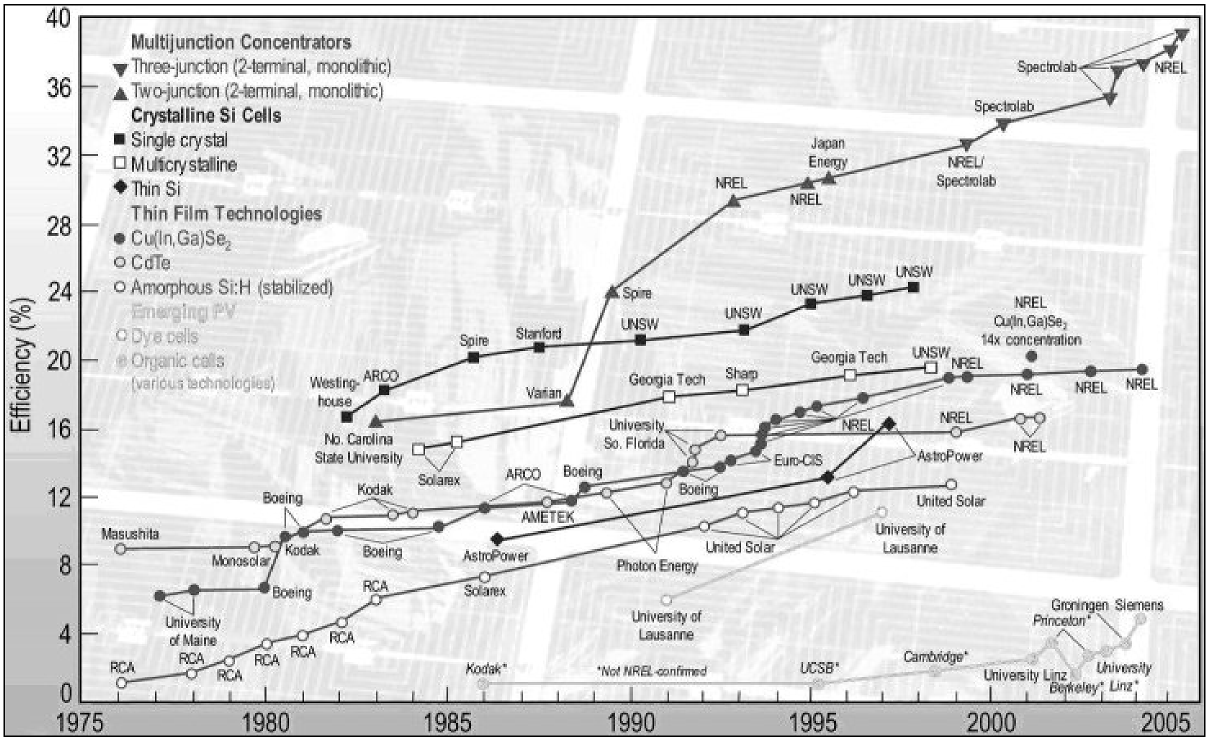


Figure 15: Chart of the Best Research Cell Efficiencies (Kazmerski and Zweibel, 2005)**.** Efficiency progression for all major terrestrial photovoltaic technologies is shown. Concentrators are the most efficient, followed generally by c-Si, CIGS, CDTE, and a-Si. Emerging technologies have the lowest efficiencies and have not been addressed in this research. This diagram also shows the developer of each technology.

It is very apparent from Figure 15 that efficiencies are steadily rising. It is also easy to see the relationship of each of the technologies. Discounting concentrator systems, clearly c-Si still maintains efficiency dominance. CIGS is the dominant thin film technology, though CdTe is not far behind. Amorphous silicon is currently the least efficient mass-produced technology, though the technology has seen continuous, steady improvements from its early development. Dye cells, based on titanium dioxide nanoparticles coated with a light-sensitive dye and surrounded by electrodes (Pinestream Communications, 2003), and organic cells, which sandwich a polymer between electrodes (Eng, 2005), are not yet efficient enough to warrant commercial production.

2.4.4. Life Cycle Analysis of Photovoltaic Technologies

This section will briefly introduce the concept of life cycle analysis (LCA) and then will cover common LCA themes for photovoltaics, including energy payback time, reduction of emissions, and social costs. The section will also discuss cadmium use in photovoltaics, recycling of modules, and subsidies.

2.4.4.1. Life Cycle Analysis

LCA is an overall cradle-to-grave environmental impact assessment of a given product. LCAs reach beyond simple pollution from use and evaluate all the environmental burdens associated with the product, including mining the ore and other elemental components, refining the product's constituents, producing the product, using the product, and ultimately disposing of the product. The International Organization for Standardization (ISO) governs LCAs under standard 14040 (Battisti and Corrado, 2005). LCAs have four main steps: "goal and scope definition," "life cycle inventory," "life cycle impact assessment," and "interpretation of results". In goal and scope definition, the purpose and audience are defined and common units of measure are determined. In the life cycle inventory stage (Figure 16), the inputs and emissions pertinent to the LCA are measured. Then in the life cycle impact assessment, the findings of the previous step are sorted and quantified. Finally, the results are analyzed and reported in the last step (Battisti and Corrado, 2005). This section will not provide a complete LCA of photovoltaic systems, but rather it will draw together analyses from existing photovoltaic LCAs.

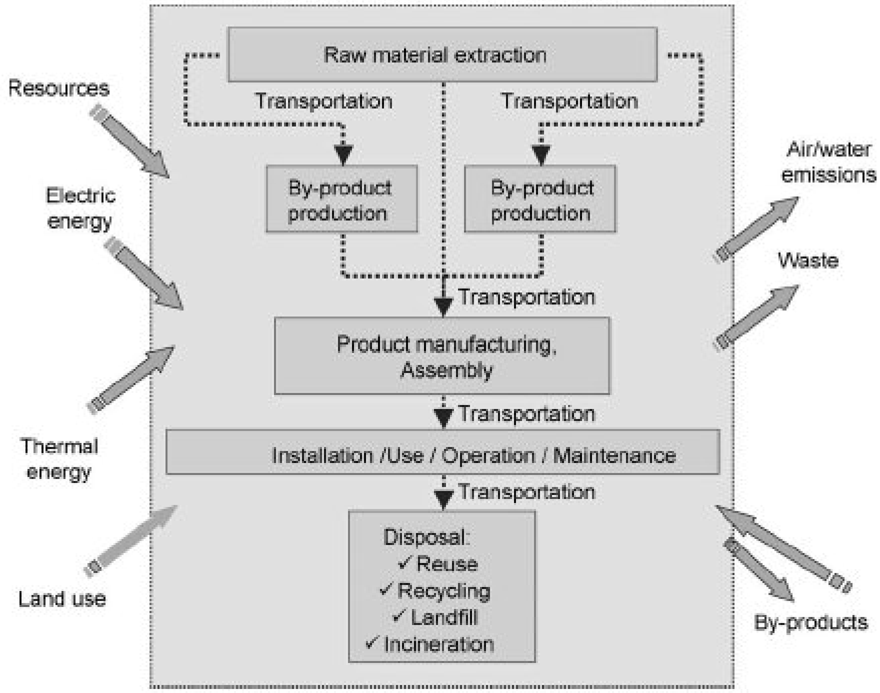


Figure 16: Elements of a Life Cycle Inventory (Battisti and Corrado, 2005)**.** The second step of a LCA is identification of the life cycle inventory. The inventory represents all the inputs and emissions during the duration of a product's life. The findings of the inventory step are sorted and quantified in the next step.

2.4.4.2. Common LCA Themes for Photovoltaics

This section focuses on common findings across all photovoltaic types, though sometimes the literature does not specify which technology was studied. Generally, the literature indicates that the benefits derived from the use of photovoltaic systems exceed the drawbacks of their production and disposal (Battisti and Corrado, 2005; Baumann et al., 1997; Bernal-Agustin and Dufo-Lopez, In Press; Fthenakis, 2003; Fthenakis et al., 2005; Pearce, 2002). It is also generally agreed that photovoltaic systems have virtually no emissions or energy requirements during normal use (Battisti and Corrado, 2005; Baumann et al., 1997; Bernal-Agustin and Dufo-Lopez, In Press; Fthenakis, 2003). Three common measurements of the value of photovoltaic systems are reported in the

LCA literature: energy payback time (EPBT), reduction of greenhouse gases and other emissions derived from the use of photovoltaics, and calculations of social costs.

2.4.4.2.1. Energy Payback Time

The first LCA measurement quantifies energy input using energy payback time. EPBT is a measure of how long a system takes to return the same amount of energy that was used to produce it (Battisti and Corrado, 2005; Baumann et al., 1997; Bernal-Agustin and Dufo-Lopez, In Press). In 1997, Baumann, et al., looked at several systems in Spain and England (Baumann et al., 1997). The Spanish system consisted of three ground-mounted, silicon-based arrays with both fixed and tracking structures. Module efficiencies ranged from 10.6 percent to 14.3 percent. For the English systems, Baumann, et al., looked at one installed, silicon-based system with a module efficiency of 13.5 percent and one theoretical, CdTe system with a module efficiency of 10 percent. Both English systems were based on BIPV placed on a surface at 25^{o} from the vertical. Baumann, et al., found that EPBT for the Spanish system was 4.3 years, while the English BIPV systems were 6.9 years and 2.3 years, respectively, for the silicon and CdTe systems. Baumann, et al., reported that integrating photovoltaics into the construction of the building as envelop materials avoided the energy required by the production of the conventional materials (Baumann et al., 1997).

In 2005, Battisti and Corrado looked at a c-Si reference system in Rome with module efficiency of 10.7 percent (Battisti and Corrado, 2005). In their study, Battisti and Corrado observed the same basic technology using four different applications: a flat roof installation; a retrofitted tilted roof installation; and two BIPV tilted roof installations. They found EPBTs to be 3.3 years, 3.8 years, and 2.9 and 3.0 years,

respectively. They also found that the energy required for electrical BOS components (inverter, cabling, electrical controls, etc.) were negligible compared to the mechanical BOS components (mounting and structural frames) (Battisti and Corrado, 2005).

Most recently, Bernal-Agustin and Dufo-Lopez examined two technologies, 13 percent module efficiency c-Si and 7 percent module efficiency a-Si, using two different applications, ground-based and roof-based (Bernal-Agustin and Dufo-Lopez, In Press). The systems were simulated in Spain. All four arrangements were assumed to be at an optimal inclination and azimuth. Bernal-Agustin and Dufo-Lopez did not account for energy used for installation, maintenance, dismantling, or recycling as these were assumed to require far less energy than module production, which the authors determined consumed 95 percent of the overall energy. The EPBT calculations accounted for fabrication of modules, aluminum frames, inverters, cabling, and support systems. Both crystalline and amorphous ground-based systems had EPBTs of 3.5 years. The EPBT of the roof-based c-Si system was 3 years, while the roof-based a-Si system was merely 2.5 years (Bernal-Agustin and Dufo-Lopez, In Press). The variances are likely not only from the differences in modules manufacturing processes but also from the associated BOS requirements.

2.4.4.2.2. Reduction of Emissions

The second common LCA measurement is quantifying the reduction of greenhouse gases and other emissions. The reduction is a comparison of the amount of emissions released during the life cycle of photovoltaic systems versus a conventional source, typically coal, oil, or nuclear power. However, since photovoltaic electricity generation by itself does not discharge emissions under normal circumstances (Battisti and Corrado,

2005; Baumann et al., 1997; Bernal-Agustin and Dufo-Lopez, In Press; Fthenakis, 2003), measurements of emissions are from the production, installation, decommissioning, and disposal or recycling of photovoltaic systems. To measure emission reduction, two assumptions generally must be expressed. First, since the measure is *avoided emissions*, the conventional energy source must be defined to establish a basis of comparison. Second, in order to distribute the emissions incurred over the photovoltaic system's lifespan, the lifespan must be established.

Baumann, et al., assumed a 25-year lifetime for their systems in Spain and England (Baumann et al., 1997). They reported only CO_2 emissions and found that the silicon, ground-based Spanish system emitted 88 tons per gigaWatt-hour (t/GWh), while the BIPV English systems emitted 143 t/GWh and 50 t/GWh, respectively, for the silicon and CdTe systems. Unfortunately, no data was provided for the Spanish conventional power source, but the English conventional power source was reported to emit 520 t/GWh, meaning that the two systems avoided 377 t/GWh and 470 t/GWh, respectively, over their lifetimes. The authors postulated that emissions would improve if module and BOS production rates increased, if manufacturers developed better production techniques, and if module efficiencies were to further improve. They also added that if photovoltaics were produced using power generated by other photovoltaics, the emissions virtually disappear (Baumann et al., 1997).

Battisti and Corrado used a different method to report emissions. Rather than providing a comparison to conventional power, the authors used the concept of payback time to determine a CO_2 payback time for their Roman system (Battisti and Corrado, 2005). Using a measure of all global warming emissions, global warming potential

(GWP), Battisti and Corrado reported a conventional Italian energy mix with GWP of 0.8 kilograms. They also assumed a conservative photovoltaic lifespan of 15 to 25 years. From this, they determined CO_2 payback time to be 4.1 years for the flat roof design, 4.6 years for the tilted retrofit design, and 3.6 and 3.9 years for the BIPV tilted roof systems. Viewing the CO_2 payback times together with the EPBTs, they concluded that "environmental payback times" are "one order of magnitude lower than their expected life." The authors went further by proposing that recovering absorbed solar thermal energy from photovoltaics would further speed payback (Battisti and Corrado, 2005).

The study performed by Bernal-Agustin and Dufo-Lopez shows the important role that the conventional energy mix plays in emission avoidance calculations. Using a module lifespan of 25 years and a typical Spanish conventional energy mix, the authors found that avoided emissions amounted to only 3.9 grams of SO_2 per kilowatt-hour (kWh), 1 gram of NO_x per kWh, 0.1 grams of particles per kWh, and 312.3 grams of CO_2 per kWh (Bernal-Agustin and Dufo-Lopez, In Press). The emissions, they wrote, were only slightly lower than average emissions of the electrical system of Spain. However, if electricity generated from photovoltaics were to replace electricity generated from that nation's worst polluter, sub-bituminous coal, then the emissions avoided increase substantially (Bernal-Agustin and Dufo-Lopez, In Press).

Krauter raises an important point when considering emissions from manufacturing photovoltaics. The author notes that often the limits of LCA studies are set at national borders, and this technique does not account for CO_2 emissions on a global scale (Krauter, 2003). Krauter points out that production, operation, and recycling are frequently performed in different global markets. Countries use vastly different mixes of

energy to produce photovoltaics (including fossil sources, nuclear energy, and renewables). Further compounding the calculation problem is the ever-changing trade of electricity in the local and global markets especially during high demand periods. Interestingly, some nations (including Brazil, Norway, and Iceland) use an energy mix with greater than 90 percent coming from renewables. In these countries, the use of photovoltaics may not make a significant difference to emissions. Consider also that if these countries employ photovoltaic technologies manufactured in countries using "dirty" electricity, then they actually reflect a negative global benefit (Krauter, 2003).

2.4.4.2.3. Externalities and Social Costs

The final common LCA measurement is the quantification of the externalities and social costs. The concept of externalities derives from the notion that "in an efficient market economy, the price of the final product should include all costs" (Bernal-Agustin and Dufo-Lopez, In Press). This, however, is not always the case in the market of electricity production. The cost of conventional electricity to the customer generally does not reflect the negative effects on public health and the environment from contamination nor effects on the climate from emissions, nor do customers' costs reflect government subsidies (Bernal-Agustin and Dufo-Lopez, In Press). In 1991, the European Union created EXTERN-E, an initiative that attempted to quantify external costs from various fuel sources, including fossil technologies, nuclear technologies, and renewable technologies (European Commission DG Research, 2001). As might be suspected, the results of EXTERN-E are hotly contested (Bernal-Agustin and Dufo-Lopez, In Press; Fthenakis et al., 2005). Fthenakis, et al., indicate that EXTERN-E paint an unfavorable picture of photovoltaics (in fact stating that photovoltaics have a higher external cost than

nuclear and natural gas energy) because the data employed are out of date (Fthenakis et al., 2005). The authors note that much of the data are from the early-1990s and figures related to heavy metals are even from the 1980s. Under environmental pressure, many photovoltaics manufacturers have cut emissions and the use of smelters in their production processes (Fthenakis et al., 2005). In an earlier publication, Fthenakis defended thin-film photovoltaics (Fthenakis, 2003). The author acknowledged that the manufacture of modules involves hazardous materials but also added that the materials can be adequately controlled with appropriate precautions. Release of hazardous materials is generally only by accident, contrary to typical fossil fuel combustion, and then could have an effect on occupational health or possibly public health (Fthenakis, 2003). Newer cell efficiencies are much higher while modules are thinner (Fthenakis et al., 2005). Lighter modules require less robust support structures and therefore use less production energy and emit fewer pollutants. Fthenakis, et al., also observed that EXTERN-E does not reflect the social costs of fossil fuel depletion, environmental damage, and subsidies, which, if included, would raise the cost of conventional electricity from 0.1 to 0.7 cents/kWh to 6 to 42 cents/kWh. Finally, the authors assert that several other factors must be contemplated when making energy source comparisons. These include

> "fiscal externalities associated with energy security (e.g., expenses of: physically protecting power plants, supply disruptions, and accident insurance); risks to energy independence and national security (e.g., control of fuel resources, depleting resources); social cost of military conflicts; unsustainability for future generations; and the risk of increased nuclear-weapon proliferation" (Fthenakis et al., 2005).

Bernal-Agustin and Dufo-Lopez did not express the same concerns with EXTERN-E but used the EXTERN-E methodology with 2002 data about Spain's energy mix to

show that photovoltaics avoided 41.2 to 91.4 m€/kWh (m€: milli-Euros… approximately $0.00095 using average 2002 conversion rate) in social costs, those being the effects on public health and the environment as a result of SO_2, NO_x, CO_2, and particle emissions (Bernal-Agustin and Dufo-Lopez, In Press). The wide range of values is due to the uncertainty of a cost associated with global warming from CO_2 (Bernal-Agustin and Dufo-Lopez, In Press).

Pearce goes on to reveal some other important social benefits of photovoltaic technologies. For instance, photovoltaics can level the playing field between developed and developing countries, and further, the manufacture of components leads to job creation (Pearce, 2002). However, he also comments on the wide range of results from typical LCAs. This he says is due to technology variations, the defined limits of the analysis (eg. some studies don't include the impacts of the BOS components or transportation of system parts), differences in local solar irradiation, and whether recycling is included in the study. He also notes that the useful life of photovoltaic systems is often assumed to be 20 years [though much literature has assumed 25 or 30 years], but photovoltaics and other solid-state devices should theoretically last indefinitely (Pearce, 2002).

2.4.4.3. Other LCA Issues

2.4.4.3.1. Cadmium

The two most promising thin-film technologies (CdTe and CIGS) contain the heavy metal, cadmium. The issue arises from the modules carrying a toxic metal in a product intended to be environmentally benign. Fthenakis and Zweibel are quick to point out that cadmium is a by-product of zinc, lead, and copper refining, and production of cadmium

consumes the waste created from the ore-processing of the other metals as Figure 17 shows (Fthenakis, 2004; Fthenakis and Zweibel, 2003). Cadmium output is mainly dependent upon the production of zinc and not the demand for cadmium (Fthenakis and Zweibel, 2003).

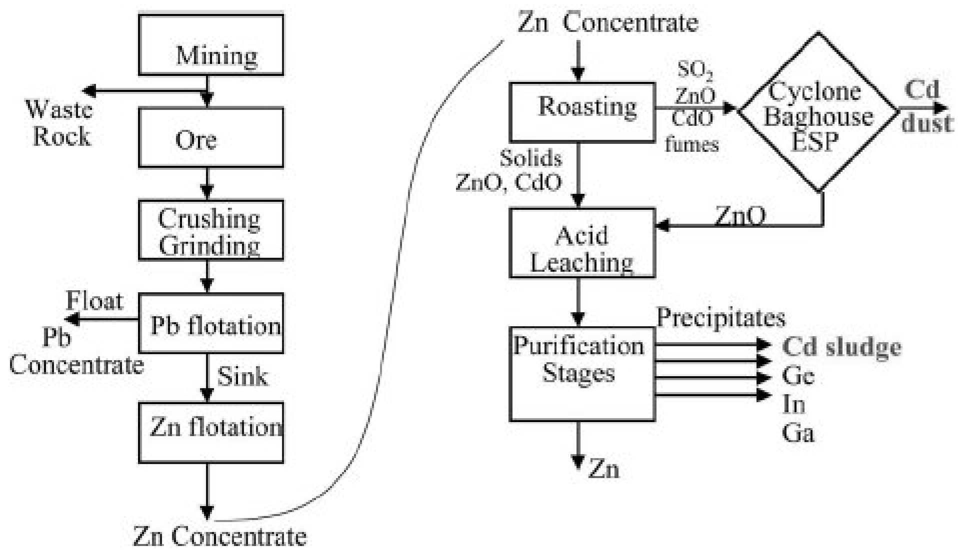


Figure 17: Cadmium Flows from Zinc Production (Fthenakis, 2004)**.** Cadmium is a by-product mainly of zinc production. Cadmium is removed in the form of dust and as sludge precipitate.

As Table 6 shows, cadmium exposure is much more likely from sources other than photovoltaics. In the table, cadmium-containing photovoltaics fall under "cadmium products." Zweibel and Fthenakis also make some comparisons that put the photovoltaics' cadmium content into perspective. For example, the amount of cadmium contained in the CdTe layer of one module is about 3 to 9 g/m^2, and the cadmium content of the CdS layer is less than 1 g/m^2 (Zweibel and Fthenakis, 2003). The two layers together contain less cadmium than one C-size NiCd rechargeable battery. When

comparing a 10 percent efficient module used for 30 years to a C-size NiCd battery recharged 1000 times over its life, the photovoltaic module uses cadmium about 2,500 times more efficiently to make electricity (Zweibel and Fthenakis, 2003). Normal-use emissions of cadmium from CdTe modules are zero while a coal-burning power plant releases a minimum of 2 grams of cadmium per gigaWatt-hour generated (assuming a well-maintained baghouse and coal with a median concentration of cadmium) (Fthenakis, 2004). Another 140 grams or cadmium per gigaWatt-hour collects as dust inside the various components of the plant. Further, the release of cadmium from photovoltaic modules is accidental, contrary to the power plant's routine emission (Fthenakis, 2004).

Table 6: Sources and Relative Contributions of Cd Exposure to Humans (in Europe) (Zweibel and Fthenakis, 2003)

Phosphate fertilizers	41.3 %
Fossil fuel combustion	22.0 %
Iron and steel production	16.7 %
Natural sources	8.0 %
Non-ferrous metals	6.3 %
Cement production	2.5 %
Cadmium products	2.5 %
Incineration	1.0 %

The accidental release of cadmium mentioned above comes primarily from two sources: structural fires and breakage (Alsema et al., 1997; Fthenakis, 2004; Zweibel and Fthenakis, 2003). Residential fires burn at approximately 800 ^{o}C to 1000 ^{o}C (Fthenakis, 2004). In a fire simulation test conducted at Brookhaven National Laboratory, strips cut from CdTe modules were exposed to heat intensities ranging from 760 ^{o}C to 1100 ^{o}C for various durations. Researches found that only 0.4 percent to 0.6 percent of the cadmium was released. Most of the metal became encapsulated in molten glass. It is believed that,

should a module accidentally make it to a waste incinerator, the cadmium would dissolve into the molten glass and be discarded as solid waste (Fthenakis, 2004).

Upon the disposal of modules in a landfill, the concern becomes breakage and leaching of cadmium (Alsema et al., 1997; Zweibel and Fthenakis, 2003). Some modules have passed EPA's Toxicity Characteristic Leaching Procedure test for non-hazardous waste, but others have not. The result appears to be dependent upon the module's manufacturer. Ideally, modules would be recycled to avoid the problem altogether (Alsema et al., 1997; Zweibel and Fthenakis, 2003).

Overall, although some emission and exposure risks exist, according to Alsema, et al., they "should not be exaggerated" (Alsema et al., 1997). The cadmium content of modules is less than or equal to "accepted products," including NiCd penlight batteries, cathode ray tubes, and plated metal sheets (Alsema et al., 1997). Hynes, et al., add that some of the materials used in production are hazardous but can be safely handled with reasonable measures (Hynes et al., 1994).

2.4.4.3.2. Optimism in Recycling of Cells and Modules

Since several authors consider recycling as a natural end-of-life process in the photovoltaic module's life cycle, it is important to note that the technology may not be quite as advanced as optimistic proponents may hope. In 1997, Alsema, et al., noted that no thin-film recycling plants existed; however, the process would be very similar to the recycling of fluorescent light bulbs and cathode ray tubes (Alsema et al., 1997). Furthermore, Alsema, et al., observed that at 1997 capacity, recycling plants would not be able to operate profitably and would, therefore, have to charge a fee to recycle photovoltaic modules (Alsema et al., 1997). Urashima, et al., note that while the

recovery of cells in experiments was between 60 and 90 percent and recovery of glass and aluminum frames was about 85 percent, the technology is still under development (Urashima et al., 2003). Krauter observes that recycling has a major impact on the overall energy input and CO_2 emissions (Krauter, 2003). This heavy weighting, along with optimistic predictions, could also be a contributor toward the variations to which Pearce referred (Pearce, 2002). Therefore, if researchers rely too heavily on optimistic estimates of recycling's potential, their reported EPBTs, avoided emissions, and economic forecasts may also be somewhat optimistic.

2.4.4.3.3. Government Subsidies

The discussion of subsidies, being economically-focused, parts somewhat from the concept of LCA; however, several authors include subsidies either in their examination of external costs (Bernal-Agustin and Dufo-Lopez, In Press; Fthenakis et al., 2005) or in a related context (Pearce, 2002). Sandén points out that photovoltaic technologies are in a no-win situation (Sandén, 2005). He says that photovoltaics are expensive because they are not commonly used, but they are not commonly used because of their high cost. A related cycle is that photovoltaics have generally weak political advocacy because of their low adoption, but their low adoption results in inadequate political backing. Sandén argues that subsidies should be used where a technology has the potential for autonomous growth and when the subsidized technology can capture future markets. Thus, subsidies should be able to decrease over time as the technology gains favor. Sandén proposes that a subsidy tax on conventional energy of $0.001 per kWh would make photovoltaics competitive by 2021 (Sandén, 2005).

Pearce takes a more aggressive position. He counters the argument that photovoltaics cannot compete economically with conventional energy sources without significant help from subsidies (Pearce, 2002). The author points out that, in the US, fossil and nuclear energy receive 90 percent of the subsidies, while photovoltaics receive only three percent. Then, still, conventional sources have the hidden costs of

> "health impacts (at least US$40 billion annually), military (US military spends between US$14.6 and 54 billion/year just defending the oil supplies in the Persian Gulf), employment, crop loss, corrosion, and global warming."

Pearce argues that if the subsidies and hidden costs were equal, photovoltaic technologies are the more economically sound energy source (Pearce, 2002).

3. Methodology

3.1. Introduction

Perhaps the most familiar and mathematically simple basis of comparison in a purchase decision is the dollar. Decision makers are interested in costs, savings, payback time, and more progressively, net present value. However, money is not always the only important element in the decision. In fact, as was discussed in Chapter 2, our nation's leaders have emphasized that other factors *should* influence the decision. When analyzed from a shallow, economic perspective, photovoltaic technologies are often at a disadvantage and do not necessarily compete successfully against conventional energy sources. For this reason, a methodology that considers abstract and complex elements must be employed. This methodology must incorporate all the relevant objectives (economic, social, environmental, etc.) in a quantifiable manner to reveal the best alternatives. Value-Focused Thinking does this very well.

This research uses Shoviak's 10-step process to develop, apply, and analyze a model to determine the best photovoltaic technologies to install at Air Force bases. This chapter will discuss Steps One through Six, which involve identifying the problem and determining the fundamental objective, developing an objectives hierarchy, developing the evaluation measures, creating the single-dimensional value functions, weighting the objectives hierarchy, and generating the alternatives (Shoviak, 2001).

In order to develop a valid model, three geographically-diverse, continental US bases were chosen to build the hierarchy. To preserve participants' anonymity, and since the actual results are not significant in the development of this model, any references to these bases will be by the region in which they are located. They will be called

Southeastern AFB, Southwestern AFB, and Northern AFB. The climate at Southeastern AFB features warm, moist summers and mild winters. The climate at Southwestern AFB is generally sunny and dry year-round. The climate at Northern AFB is cooler on average with moderate precipitation. Once the hierarchy was put together, only one base, Northern AFB, was used to generate SDVFs, value weightings, and alternative scores.

This model is built around the Base Civil Engineer (BCE) as the decision maker. Although the BCE is the decision maker, the BCE receives advice and recommendations from subject matter experts (SMEs) within the squadron. At each base in the study, the SMEs provided the basic details, including objectives, hierarchy elements, and evaluation measures.

3.2. Step One: Identify the Problem and Determine the Fundamental Objective

Federal agencies are required by Executive Order 13123 to strive to increase their use of renewable energy (Clinton, 1999). One particularly promising renewable energy source is solar energy converted to electricity by solar photovoltaic panels. Previous research by Duke developed a model to help determine generally which renewable source (wind, solar, or geothermal) is the best alternative at a given Air Force base (Duke, 2004). This research assumes that the best renewable source is solar electricity and now aims to determine what specific types of systems (rooftop, fielded array, etc.) are the best options. The fundamental objective of the VFT model is to determine, based on a decision maker's value system, the best photovoltaic technology alternatives for an Air Force base.

3.3. Step Two: Develop an Objectives Hierarchy

To develop the objectives hierarchy, the BCEs at all three bases were asked for SMEs with backgrounds in energy management, environmental management, and contract management. Those SMEs were asked two general questions. First, what objectives are important when evaluating a potential new source of electricity for the base? Second, what objectives are important to site construction for renewable energy sources or retrofitting facilities? These questions returned several responses that became the basis of objective development. Selected responses are shown in Table 7 in no particular order.

Table 7: Selected Responses Used to Generate Objectives

- "If these are going to be put on a building roof, this would mean a structure analysis, and probably some reinforcing."
- "There probably would be a periodic cleaning cycle to keep the pollen, dirt, soot, (from the field clearing fires in this area), and birds off the units. And there is always grass cutting."
- "What is the availability of spare parts?"
- "It looks like to do this right, a "PV farm" area had to be selected where one big PV installation could be built, rather then spreading small units all around the site."
- "The training to maintain PVs may be more then what the maintenance shop could handle. The turn-over in military electricians would be a problem."
- "Can this be utilized for publicity to show our awareness of energy utilization and reduction?"
- "Is the new system green power or renewable energy source?"
- "I look at source reduction, which in this case means either reducing energy demand on the grid or purchasing 'green' power."
- "The critical mission of the AF does not allow the use of technology which is in any way experimental."
- "The ideal energy generation system is one that you don't know exists unless you have to work with it."
- "How 'hot' is energy conservation at the present time? Have we had recent increases in oil / natural gas prices? Has the president just given a speech supporting renewable energy? Has the president recently passed any energy bills that support renewable energy?"
- "We want to lead the pack not be pushed."
- "The AF core mission is to fly planes, not to operate energy generation systems."

Although the alternatives were already generally known (albeit not well defined at this stage), this process reflected a top-down approach (Keeney, 1992; Kirkwood, 1997) and had the potential of revealing many more objectives than those related only to photovoltaic technologies. This top-down method allowed for attributes favoring other energy sources, including conventional grid power (the "Do Nothing" alternative) and other renewables, resulting in a true and balanced model for choosing the best energy source. The responses were generally categorized into three main fields: those dealing with economic factors, those related to environmental aspects, and those pertaining to the physical operation of a new system. The fundamental objective and first-tier values are shown in Figure 18.

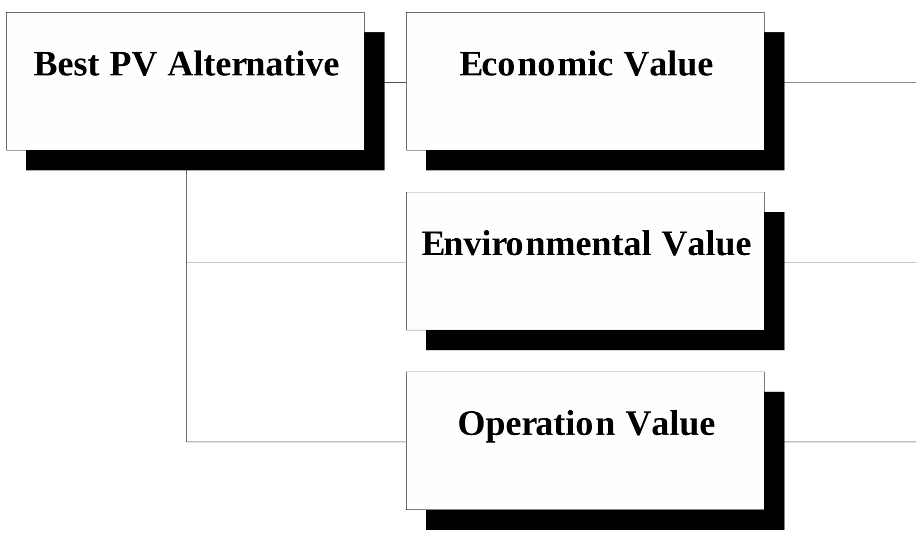


Figure 18: First Tier of the Value Hierarchy. The first tier of the value hierarchy is divided into Economic Value, Environmental Value, and Operation Value.

3.3.1. Economic Value

Economic value is the heading given to any objective related to financial considerations. These include installation costs, projected annual maintenance costs, projected annual savings benefit, and system longevity. Although these are all separate values, they are combined and evaluated under one single value, namely Maximize Savings Ratio. The individual components values of Maximize Savings Ratio are discussed further. Figure 19 shows an expanded view of the Economic Value.

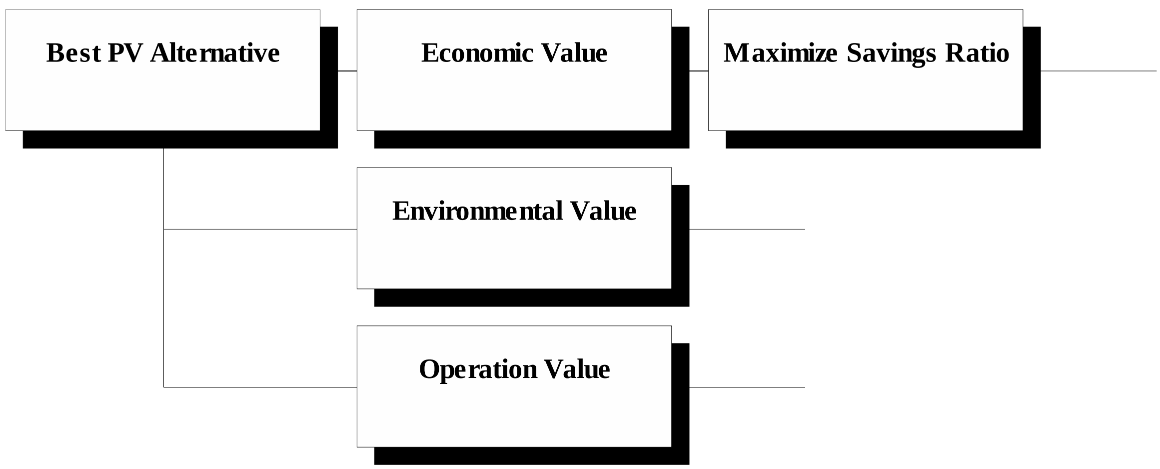


Figure 19: Value Hierarchy with an Expanded View of the Economic Value. The Economic Value has been expanded to show its second-tier value.

3.3.1.1. Minimize Installation Cost Value

Installation costs are made up of two elements: the cost of purchasing the physical system and the cost of special site construction. The cost of the physical system includes photovoltaic modules, inverters, line conditioners, and cabling, and it can be readily quoted by any supplier or may be approximated based on system capacity. Special site construction includes vegetation clearing, ground leveling and compaction, foundation

and support structure construction, building and roof reinforcement, and any other site-specific construction or improvement. Special site construction may also be quoted by an installer or estimated using references such as the R.S. Means Building Construction Cost Data manual (RS Means Engineering Staff, 2005a).

3.3.1.2. Minimize Projected Annual Maintenance Cost Value

Maintenance costs are those that keep the system running at expected capacity up to and beyond its expected lifespan. For photovoltaic systems, these include module dust and snow removal, grass cutting, and routine inspection. Other energy technologies may have their own requirements. Since maintenance costs will primarily be labor-related, these costs may be estimated based on existing contracts (as in the case of grass cutting) or from other labor cost estimating tools including R.S. Means Facilities Maintenance and Repair Cost Data manual (RS Means Engineering Staff, 2005b).

3.3.1.3. Maximize Projected Annual Savings Benefit Value

The savings benefit is the amount of money estimated to be saved by the use of the installed technology. Once the technology is up and running, it will be generating new electricity to contribute toward the base's electrical supply. Thus, the base will require less total electricity to be purchased from the grid. This amount is measured based on total system capacity, historical local climatological data, system orientation and tilt angle, and expected cost of grid-supplied electricity.

3.3.1.4. Maximize System Longevity Value

System longevity is an estimate of how long the system will last. In order to reap an economic benefit from purchasing and installing a new system, the system must be

available and efficient for a period of time. This duration is discussed in much of the literature and has been discussed in Chapter 2.

3.3.2. Environmental Value

The environmental portion of this model is significant as it was the federal interest in green technologies that drove the research. The environmental factors that SMEs found important were the environmental benefit of consuming "green" electricity, the positive public image generated from employing green technologies, and the possible negative consequences of installing a system. Figure 20 shows an expanded view of the Environmental Value.

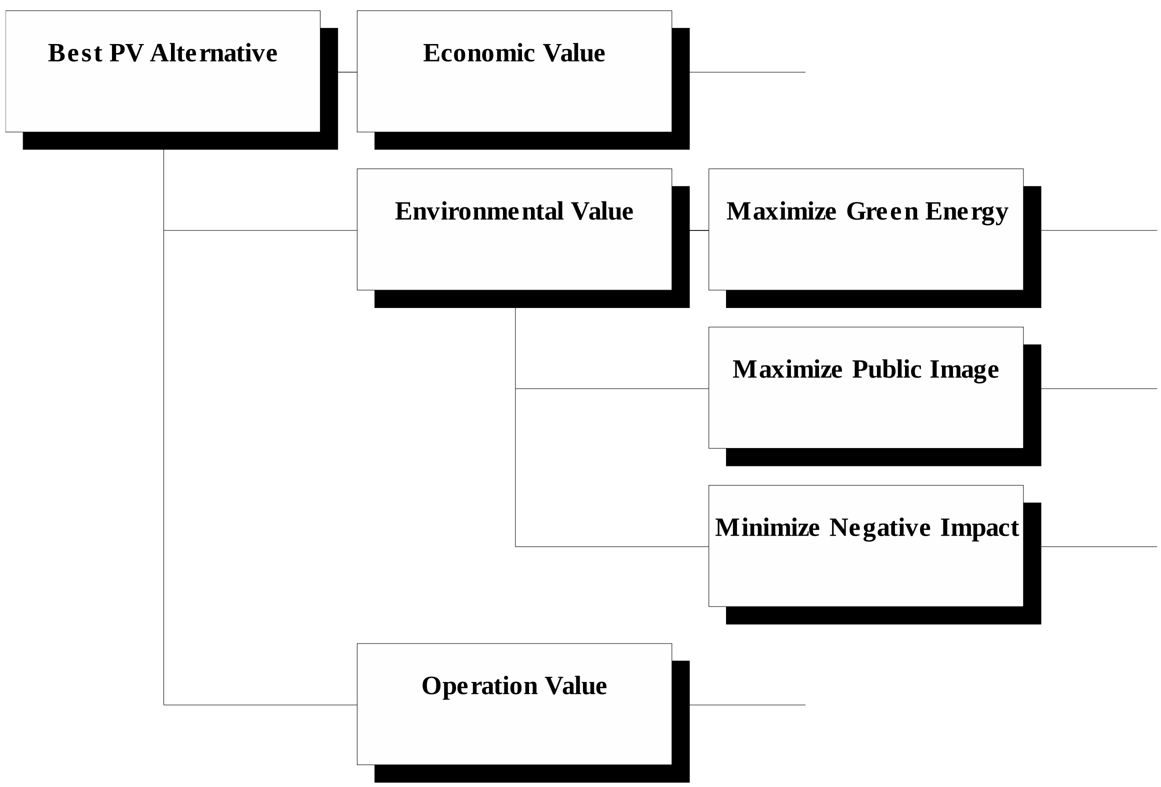


Figure 20: Value Hierarchy with an Expanded View of the Environmental Value. The Environmental Value has been expanded to show its second-tier values.

3.3.2.1. Maximize Green Electricity Value

Green electricity is electricity generated from renewable sources, including solar, wind, geothermal, and biomass, among others. The consumption of green energy in lieu of conventional energy has many positive effects depending upon the source of the conventional energy. Generally, green energy does not contribute significantly during its operation to atmospheric greenhouse gases, toxic metal emissions, nor other hazardous wastes including radioactive contaminants. Green energy is sustainable and may enhance the nation's energy independence and national security as discussed in Chapter 2. For these reasons and many others, consuming a greater portion of green energy is progressive.

3.3.2.2. Maximize Public Image Value

Public image is important to commercial entities as it is strongly related to shareholder profits. However, shareholder profit is not a factor for government agencies. Instead of reporting profits to shareholders, government agencies must demonstrate frugal use of taxpayers' money. The public may consider it a good use of tax funds to invest in a renewable energy system. The public may also be glad that its government is leading the way when it comes to energy conservation.

3.3.2.3. Minimize Negative Impact Value

Installing a photovoltaic system on an Air Force base, like any new construction, has the potential of triggering a negative impact on the local environment, including endangered species, cultural resources, and critical habitats. Renewable energy is generally expected to have a positive environmental effect. If green power will be generated at the expense of the local environment, then the new system may no longer be

an attractive proposition. Further, any system that could cause more damage to the environment than benefit to the Air Force should be carefully considered.

3.3.3. Operation Value

Operation values are any non-economic factors related to operating and sustaining the new system. These include the life cycle operation of the system, reputation as represented by the manufacturer's business strength and the working record of the technology, system complexity, system intrusiveness, and operation risk. Figure 21 shows an expanded view of the Operation Value.

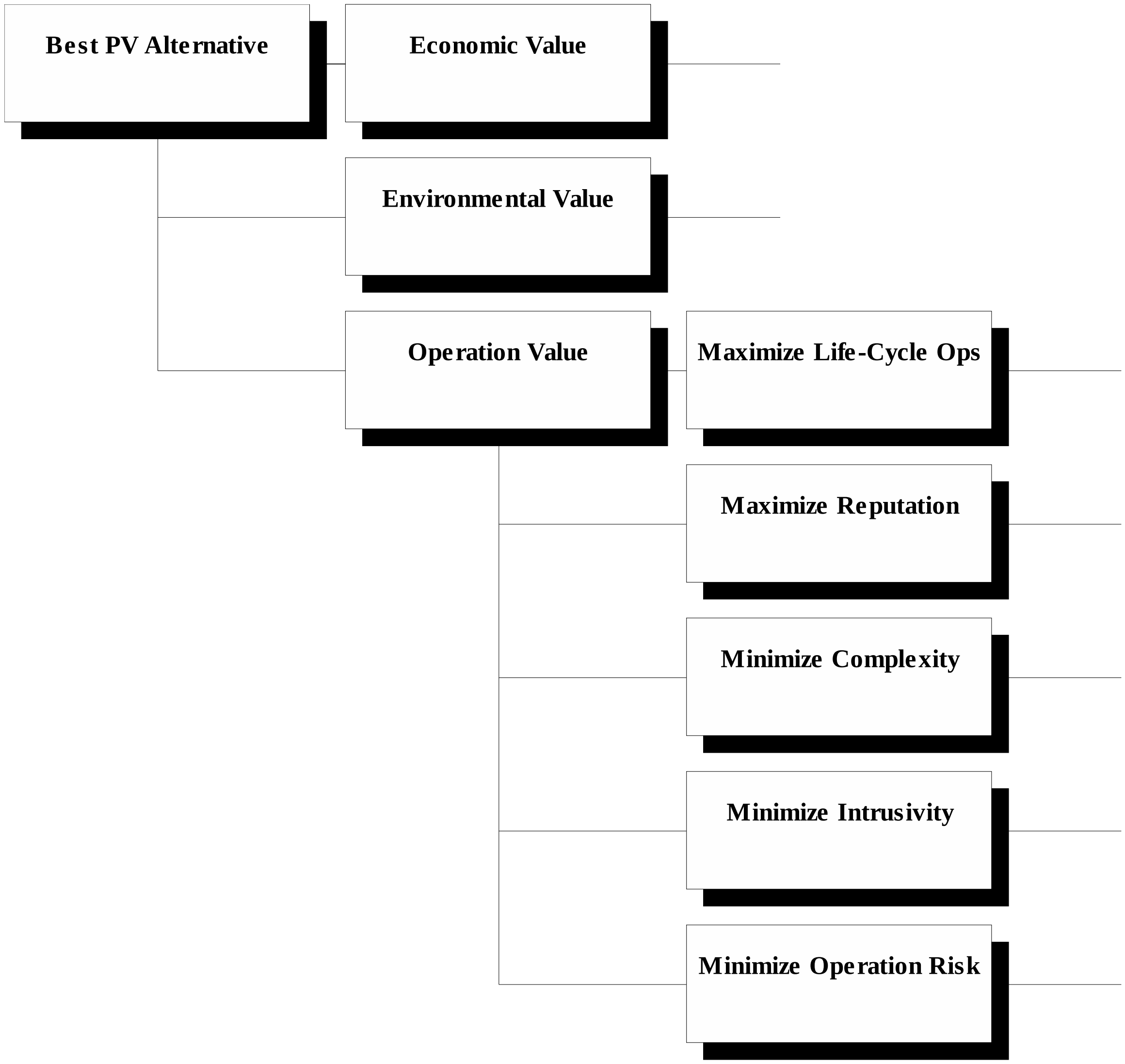


Figure 21: Value Hierarchy with an Expanded View of the Operation Value. The Operation Value has been expanded to show its second-tier values.

3.3.3.1. Maximize Life cycle Operation Value

Components may break or become damaged from a number of causes over time. The ability to switch out damaged parts as necessary in a swift manner will help keep the system running smoothly.

3.3.3.2. Maximize Reputation Value

Reputation has two components: the manufacturer and the technology in general. The manufacturer is important since this relates to component quality and warranties, customer service and support, and the ability to respond to future needs, as well as many other factors. The specific technology also plays a key role since it is constantly evolving. There are many factors that affect performance differently in each technology. Purchasers of an expensive system will want to be reassured that the technology can be reasonably expected to perform as specified.

3.3.3.3. Minimize System Complexity Value

Generally, the systems considered in this research have few moving parts and fairly common electrical components, with the exception of the specialized modules themselves. That being the case, photovoltaic systems are still rather complex and unfamiliar to most people. The mere appearance of complexity, even if overstated or unfounded, may be enough to drive down interest in the system. It is, therefore, important to address the real or perceived complexity in some productive way to minimize its effect.

3.3.3.4. Minimize Intrusiveness Value

As one SME commented, “The ideal energy generation system is one that you don't know exists unless you have to work with it.” Intrusiveness refers to mission impact, visual disturbances, and land-use issues. With mission impact, the primary concern is the effect on flying operations and flight safety. Glare off of photovoltaic modules near the flightline could affect pattern flight operations, and system frangibility issues could result in more serious pilot injury or greater aircraft damage in the event of a flight mishap.

Visual disturbances are mainly an aesthetic issue. Some system installation strategies may be considered more unsightly than others (a field array, for example, versus a roof installation). Finally, land consumed by a large field array cannot be used for much else. This presents base expansion problems if not properly addressed.

3.3.3.5. Minimize Operation Risk Value

One of the SMEs pointed out that the Air Force is not in the business of producing electricity. Budget cycles can change from year to year, and a base may not be able to afford to adequately operate and maintain a photovoltaic system if the funds will be cut at some point in the future. Further, the military in general has high personnel turnover, and individuals initially trained to operate and maintain such a technical system may depart, taking with them their knowledge and experience. Given these circumstances and others, it may be less risky to leave the ownership, operation, maintenance, or any combination thereof to someone else.

3.4. Step Three: Develop Evaluation Measures

In this research, evaluation measures often followed naturally from the objectives that they measured. Only one value, Maximize Reputation, had more than one measure. The Economic Value Measure discussed in 3.4.1 below comprises a single measure, but it is actually made up of several elements. The text in parentheses following each measure name is the name used to describe the associated SDVF in Step Four and in the Microsoft Excel model.

3.4.1. Economic Value Measure

3.4.1.1. Maximize Savings Ratio Measure ("Savings Ratio")

Systems with widely varying up-front costs, maintenance costs, annual benefits, and longevities are difficult to compare without deeper analysis. The Savings Ratio consolidates several economic measures and reports them in a common, dimensionless scale. The Savings Ratio is calculated as shown in Equation 3, and Future Value is calculated as shown in Equation 4.

$$SR = \frac{FV(Savings_{Annual})}{Cost_{Initial} + FV(Cost_{Annual})} \tag{3}$$

where

$FV(Savings_{Annual})$ is the future value of the annual savings (benefit), and
$FV(Cost_{Annual})$ is the future value of the annual cost (maintenance).

$$FV(x) = \sum_{t=1}^{L} \left(x \times (1+i)^t \right) \tag{4}$$

where

x is the amount annualized (in today's dollars),
L is the expected system longevity (in years), and
i is the expected inflation rate.

If the Savings Ratio is less than one, then the total costs exceed the total benefits; if the Savings Ratio is equal to one, then the total costs equal the total benefits; if the Savings Ratio is greater than one, then the total costs are less than the total benefits. The future value function is closely related to the present value function. Future values are used in Equation 3 rather than present values since the calculation returns the future value of the savings or cost in present-day dollars. This allows for inflated costs and savings for

future years as opposed to reduced costs and savings as would be the result of using the present value function.

The Savings Ratio calculation includes several user-defined assumptions that are implied in Equation 3. The user-defined values are shown in Table 8.

Table 8: User-defined Values in Savings Ratio Calculation

Value	*Description*
System Capacity	Size, in kW_p, of the system under review; same as "DC Rating" in Table 9
Annual Savings	Expected annual benefit from purchasing less grid electricity; from PVWATTS calculator
Special Construction Cost	Cost of site preparation, foundation construction, building reinforcement, etc.
Installation Cost	Sum of "Special Construction Cost" and "Physical System Purchase Cost" (defined later; based on a user-defined cost per kW_p)
Annual Maintenance Cost	Expected annual maintenance cost, including cleaning and grass-cutting (based on a user-defined cost per / kW_p)
Electricity Cost Increase Rate	Expected rate of change in electricity cost over and above regular inflation
Maintenance Cost Increase Rate	Expected rate of change in maintenance cost over and above regular inflation
Lifespan	Expected longevity of the system

"System Capacity" is the rated size of the system in DC electricity. This value is the same as that used in "DC Rating" in Table 9. This is the "nameplate" (USDOE EERE, ND) rating and does not guarantee any particular output. System output also depends upon the factors listed in Table 9.

The PVWATTS calculator associated with "Annual Savings" in Table 8 is an online calculator developed by the National Renewable Energy Laboratory (NREL) to provide performance estimates and electricity generation calculations for grid-connected systems in the United States (USDOE EERE, ND). The calculator uses hourly

meteorological data from 1961 through 1990 to estimate average monthly electrical energy produced for a crystalline photovoltaic module. The result is best understood to reflect an average annual, long-term output rather than specific performance data in any given year (USDOE EERE, ND). Although the calculator was developed for crystalline photovoltaic modules, it will provide a generally conservative (lower) estimate of savings for thin films provided the temperature coefficient of the module (efficiency loss as module temperature rises (see 2.4.1.3.2 above)) is equal to or less than 0.5% per ^{o}C (Marion, 2006). PVWATTS requires several values to return a valid result. The necessary values are shown in Table 9.

Table 9: PVWATTS' Required Values (USDOE EERE, ND)

Value	*Description*
DC Rating	Size, in kW_p, of the system under review; same as "System Capacity" in Table 8
DC to AC Derate Factor	A factor to account for system efficiency losses resulting from module mismatches, inverters, connections, wiring, dirt buildup and snow, system availability, etc.; the default factor is 0.77
Type of PV Array	A list from which to choose a fixed array or one- or two-axis tracking
PV Array Tilt Angle	The angle of tilt as measured from the horizontal plane (eg. An array on a roof with a pitch of 'four in twelve' will have a tilt angle of $\tan^{-1}(^{4}/_{12}) = 18^{o}$.)
PV Array Azimuth Angle	The clockwise angle from true North
Local Electric Costs	The current, local cost of purchasing electricity from the grid

With the exception of "DC to AC Derate Factor," all values are specific to the case under analysis. Once all of the required fields have been completed, PVWATTS will return the average monthly and annual AC electricity generated as well as cost savings from installing the system, which is then used to calculate the numerator in Equation 3.

The “Installation Cost” of Table 8 is the sum of the “Special Construction Cost” and the “Physical System Purchase Cost.” The “Special Construction Cost” value in Table 8 is specific to the case under analysis and may be estimated using any practical method (i.e. cost reference manual, rule-of-thumb, contractor estimate, etc.). In this analysis, the cost is based on the 2006 *RS Means Building Construction Cost Data* manual (RS Means Engineering Staff, 2005a).

The “Physical System Purchase Cost” is a highly variable quantity involving several factors beyond the scope of this research. Even among similar technologies, manufacturer cost variations of 10 to 20 percent are not uncommon (von Roedern, 2006). Generally, manufacturers’ cost data is difficult to obtain. The technology costs to be applied in Equation 3 and shown in Table 10 are from NREL estimates provided in personal communications with NREL (von Roedern, 2006). NREL compiles manufacturers’ cost data when it is available. The “*Cost Range*” shown in Table 10, column 2 assumes a large purchase of 30 kW_p or more worth of modules (von Roedern, 2006). The cost shown in column 3 is an average of the range and will be used for all cost calculations when the system is 30 kW_p or larger. The cost shown in column 4 reflects a 10 percent surcharge added for systems smaller than 30 kW_p.

Table 10: Estimated Module Costs (von Roedern, 2006)

Technology	*Cost Range* (\$ / W_p)	*Equation 3 Cost* ($\geq$30kW_p) (\$ / W_p)	*Equation 3 Cost* (<30kW_p) (\$ / W_p)
c-Si, CIGS	3.50 – 3.75	3.63	3.99
CdTe, a-Si	2.40 – 2.80	2.60	2.86

Like the Special Construction Cost, the “Annual Maintenance Cost” is specific to the system being assessed and may be estimated using any practical method. In this

analysis, the annual maintenance cost is a user-defined value, in the form of $ / W_p, that will be determined by rule-of-thumb. It will be shown in 4.4.2 of the sensitivity analysis that, at Northern AFB, only values less than $5 / kW_p have any effect on the final ranking, and then only when the actual current cost of electricity is inflated by nearly 250%.

The Savings Ratio calculation, as the name implies, returns a ratio value rather than a dollar value. This model assumes that benefits and costs in the ratio are equally affected by inflation. Therefore, it would normally be unnecessary to discuss inflation as an important factor in the ratio as long as the inflation rates in the calculation are equal, since they will have no effect on the outcome. However, it may be established that benefits and costs are not affected by inflation at the same rate. Then it will be necessary to include separate inflation values for benefits and costs. A sensitivity analysis will reveal what effect, if any, different inflation rates have on the final alternative ranking. This is the purpose of including the "Electricity Cost Increase Rate" and the "Maintenance Cost Increase Rate." By adjusting these values, the user may study the effects of differing rates of inflation. No maintenance price projections nor historical costs are available; however, although maintenance and construction use somewhat different resources, it may be helpful to know for comparative purposes that construction inflation in the last three years has varied between 2.5 percent and 8.9 percent (RS Means Engineering Staff, 2005a). The Consumer Price Index has varied from 2.1 percent to 3.2 percent during the same period (U.S. Department of Labor Bureau of Labor Statistics, 2006). On the other hand, projected real electricity costs are expected to decline 6.6 percent from 2004 through 2015, but real costs are then expected to return to their 2004

levels by 2030 (USDOE Energy Information Administration, 2006). In other words, electricity costs are expected to keep pace with inflation between 2004 and 2030.

"Lifespan" is the duration of time that the system is expected to produce electricity. As mentioned in 2.4.4.2.3 above, photovoltaic modules are solid-state devices that could be reasonably expected to last indefinitely. The literature typically estimates lifespans of 25 to 30 years. The initial value used in this model is 30 years. A sensitivity analysis will examine other lifespans.

3.4.2. Environmental Value Measures

3.4.2.1. Maximize Green Electricity Value Measure ("Percent Green Electricity")

Green electricity use can be measured as a percentage of total electricity consumed. Most electric utility companies produce and sell electricity that comes from several sources, one of which may be green. The average energy mix is sometimes reported on the internet and in billing statements.

When an Air Force base chooses to install and utilize its own green energy system, this will have an effect on the total green energy used at the base. For example, assume a base consumes 1 GWh of electricity each year. Initially, all of this electricity is purchased from the local utility, which hypothetically produces two percent of its electricity from green sources; thus, the base utilizes two percent green electricity. The base then constructs a photovoltaic system which produces, on average, 500 kWh of green electricity per year. Now the total portion of green energy consumed rises, reflecting a 2.45 percent increase of green energy usage at the base (see Appendix D for

the calculation). The measure used to quantify the "Green Electricity Value" is the percent of the total consumed electricity that comes from all green sources.

3.4.2.2. Maximize Public Image Value Measure ("Newsworthiness")

As mentioned in 3.3.2.2 above, the public may consider investment in renewable energy systems a good use of tax funds. To proudly announce this type of investment, decision makers may want to use a Public Affairs press release. The Public Affairs office decides whether or not information is newsworthy based on several factors, including local proximity, oddity, and technological development (Michele, 2006). Another important consideration is the photographic potential. For an announcement to warrant a photo, it must involve something interesting and visually appealing (Michele, 2006). Depending upon the importance of the news item, the press release may have several different formats and audiences. The measure for "Public Image Value" uses a qualitative (categorical) scale rather than a quantitative (continuous) scale.

3.4.2.3. Minimize Negative Impact Value ("NEPA Actions")

The federal government has a process in place to ensure that the benefits of a particular action on federal property exceed the negative impacts, or at least are soundly justified. The process is called NEPA, and it gets its name from the law that requires it: National Environmental Policy Act. NEPA ensures that the federal government is acting as a good steward of the environment by considering the direct and indirect effects on endangered species, protected habitat, and cultural resources before any action is taken (Johnson, 2006). The NEPA process involves several levels. First, under certain circumstances, a project could qualify for a Categorical Exclusion (CATEX) from having to continue in the NEPA process. If a project does not qualify for CATEX, an

Environmental Assessment (EA) or an Environmental Impact Study (EIS) must be performed depending upon project scope and potential environmental impact. The process could then have any of three results. First is a Finding of No Significant Impact (FONSI). Second is a Finding of No Practicable Alternative (FONPA), which means that there is an impact, but the benefit outweighs the impact. Third, the impacts could outweigh the benefits, and the project is terminated (Johnson, 2006). The measure for the Negative Impact Value is categorical based on likely NEPA scenarios for given alternatives.

3.4.3. Operation Value Measures

3.4.3.1. Maximize Life cycle Operation Value Measure ("Local Suppliers")

The measure that quantifies the value Life Cycle Operation is a count of the number of parts suppliers within a defined radius of the base. The distance is specified by the decision maker at each individual base. Most parts will either be shipped by the supplier or physically transported by base personnel. In either case, the farther from the base that the suppliers are located, the greater the base's financial and logistical burden for procuring spare parts. The distance also affects how long it will take to receive a part, and if the system operates at reduced capacity or not at all while awaiting the part, the delay may have a great impact.

The number of suppliers within the defined radius can be found by searching an appropriate business directory. This model uses the Momentum Technologies, LLC, Source Guides at http://www.sourceguides.com/index.html. The number of suppliers is found by navigating through the Source Guides as detailed in Appendix E. Momentum Technologies, LLC, Source Guides are not necessarily all-inclusive, as businesses must

ask to be listed (Momentum Technologies LLC, 2005). There are several other business directories that could be used to find photovoltaic parts suppliers, including local telephone books. The inclusion of the Momentum Technologies, LLC, Source Guides is in no way an endorsement of that particular directory.

3.4.3.2. Maximize Reputation Value Measures ("Manufacturer Longevity"; "Proven Technology")

The Reputation Value is the only value in the model with two measures. The first relates to the manufacturers historic success in running a business (and hopefully, future success). Although analyzing corporate financial data might yield a better projection, this measure tracks how long the manufacturer has been in business, a much simpler measure. The second measure relates to the experience level of the technology. This measure is calculated by multiplying the number of systems of a particular type by the number of years they have been operating. The result, in system-years, is a measure of how many combined years the technology has been used. An analogy is a business that has three experts, each with 10 years of experience. The business then declares it has 30 years of combined experience.

3.4.3.3. Minimize System Complexity Value Measure ("Initial Training")

Technicians working on almost all systems, new and existing, require some amount of introductory and continuation training. Training helps transition novice technicians who may fear an unknown technology to experts who feel comfortable working hands-on with the system. Training is also important because it may help reduce the chance of an on-the-job injury or death. It helps protect equipment and hardware from damage and deterioration. The act of training, however, consumes valuable resources, especially time

and money. Effective training must, therefore, strike a balance between training value and resource commitment. The amount of initial training that each system requires depends upon the current proficiency of the technicians and is, therefore, specific to each base. The measure is continuous and is based on the approximate number of hours of training to help technicians feel comfortable with the new system.

3.4.3.4. Minimize Intrusiveness Value Measure ("Intrusivity Level")

Intrusiveness is measured in a categorical manner based on anticipated impacts from various alternatives. These include no impact, impact to flight operations, impact on land use when within proximity to occupied areas, and combinations thereof. Rooftop applications are considered to have negligible impact on land-use.

3.4.3.5. Minimize Operation Risk Value Measure ("Own-Operate-Maintain")

As mentioned in 3.3.3.1 above, a base might determine that owning, operating, and maintaining a photovoltaic system causes more risk or hardship to in-house employees and the Air Force than the base is willing to assume. Thus, a base could continue to own the system, but hire a contractor to operate and maintain it, such as through an Energy Savings Performance Contract (ESPC). Another option is to lease the land to the local utility such that the utility owns, operates, and maintains the system. Still another option is for the utility to own the system on federal property, while contracting with a third party to operate and maintain the system. Each setting offers differing levels of risk. The measure is categorical based on potential solutions for given alternatives.

The entire expanded hierarchy is displayed in Figure 22.

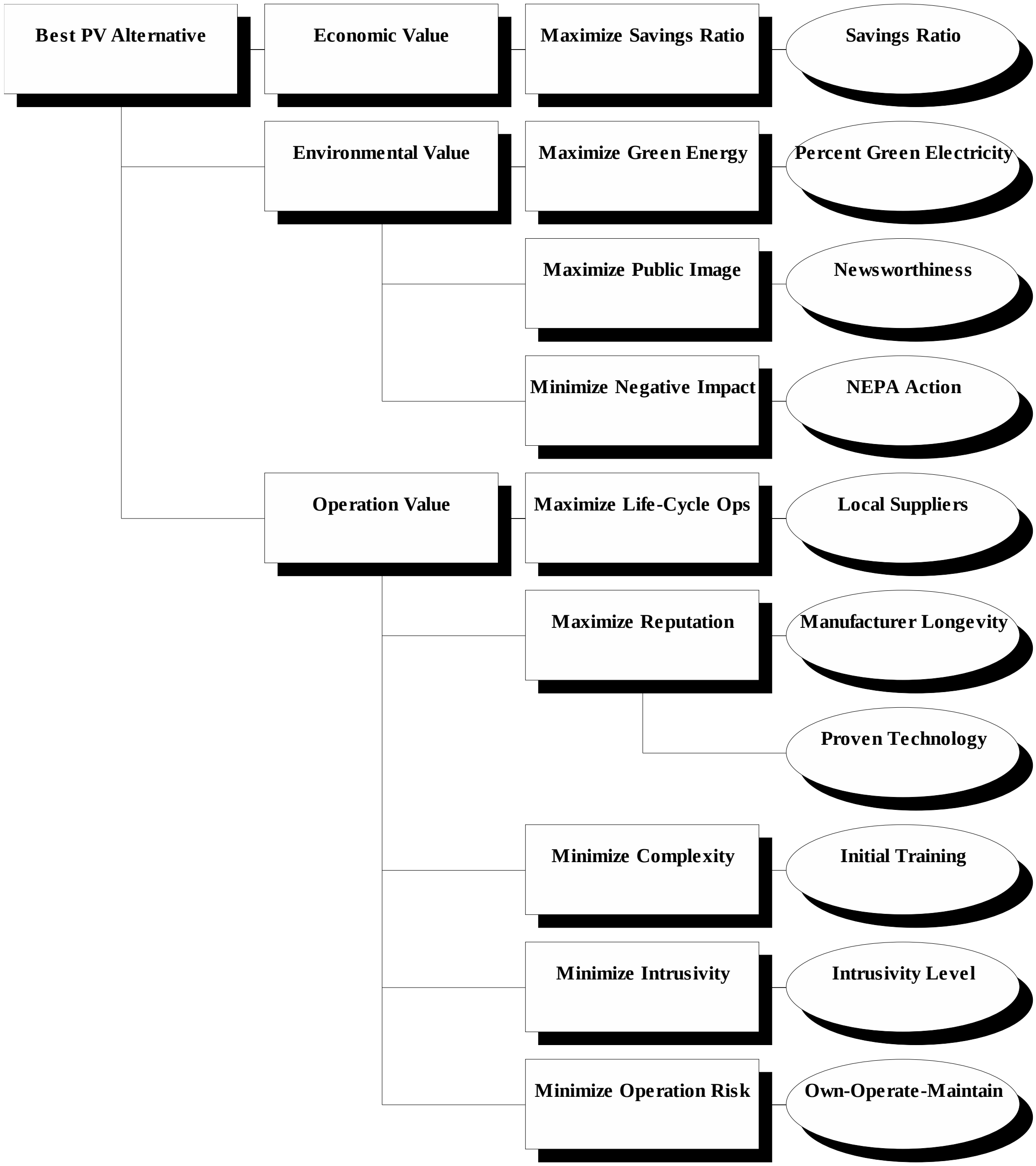


Figure 22: The Complete, Expanded Hierarchy. Shown is the complete hierarchy for choosing the best photovoltaic alternative, including first- and second-tier values and evaluation measures.

3.5. Step Four: Create the Single-Dimensional Value Functions

Through Step Three, the 10-step process created a generic value hierarchy with generic evaluation measures. These can be applied at any base. However, beginning

with Step Four, each individual base would proceed down its own path. Therefore, beginning with Step Four, only the inputs from one base, Northern AFB, will be used to complete the model.

3.5.1. Quantitative and Qualitative Single-Dimensional Value Functions

As alluded to throughout 3.4 above, SDVFs can be either quantitative or qualitative, depending on the nature of the measure. In any case, the function must either monotonically increase or monotonically decrease. This means the function must indicate continuous increasing preference or continuous decreasing preference, but a single function cannot locally increase and locally decrease across its range (Kirkwood, 1997).

3.5.1.1. Quantitative Single-Dimensional Value Functions

Quantitative, or continuous, SDVFs are defined either by a piecewise linear function or by an exponential function with no practical difference between the two forms (Kirkwood, 1997). In both quantitative functions, the lower limit and upper limit must first be defined. When the lower limit is also the least preferred case, then the function is increasing. When the lower limit is the most preferred case then the function is decreasing (Kirkwood, 1997). Any score less than the lower limit receives the same value as the lower limit. Likewise, any score greater than the upper limit receives the same value as the upper limit. Some representative increasing SDFV shapes are shown in Figure 23.

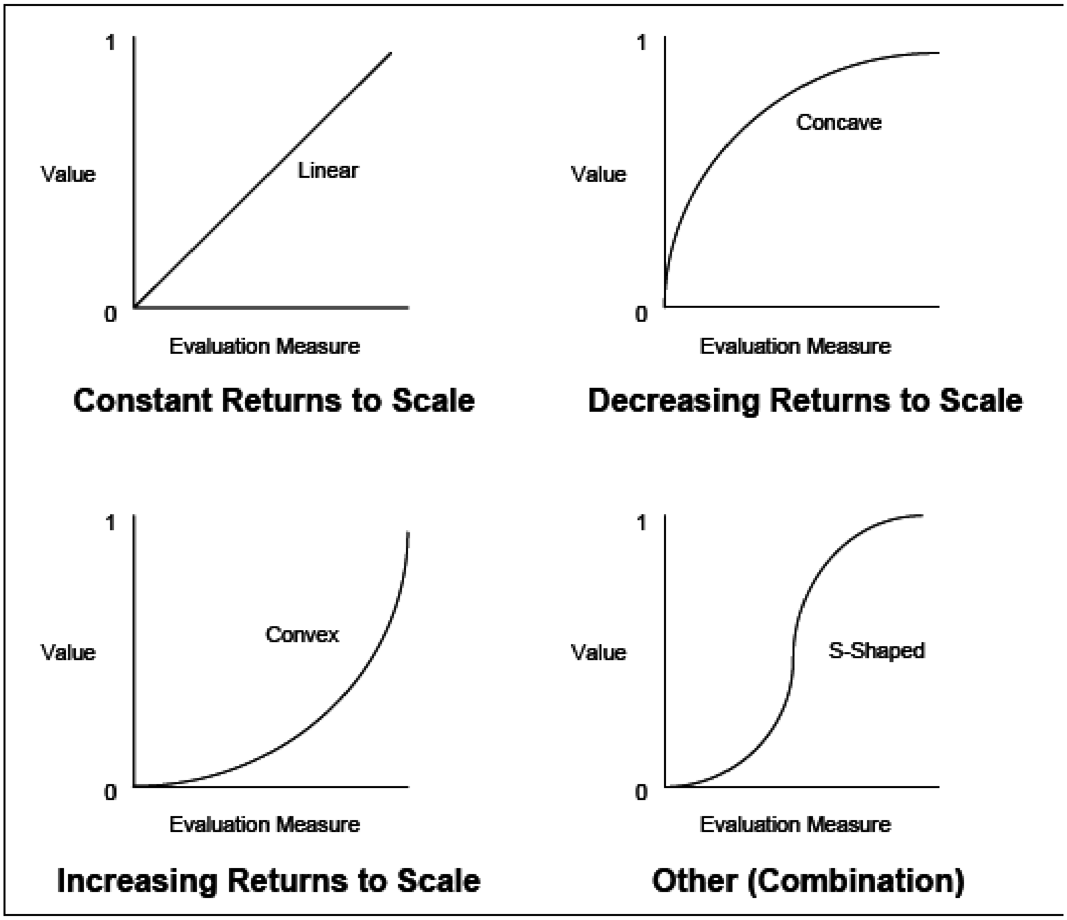


Figure 23: Shapes of Increasing SDVF (Jeoun, 2005)**.** SDVFs can take many shapes as long as they are either continuously increasing or decreasing.

Piecewise linear functions assume a constant increment between defined score levels. They are represented by jagged-looking functions as the line segments change their slopes at the defined score levels.

When the continuous function is defined by more line segments than is practically represented by a piecewise linear function, then an exponential function serves as a better approximation (Kirkwood, 1997). Exponential functions are defined by equations of particular form as shown in Equations 5 and 6 (Kirkwood, 1997).

$$v(X)=\begin{cases}\dfrac{1-e^{\frac{-(X-Low)}{\rho}}}{1-e^{\frac{-(High-Low)}{\rho}}}, \rho \neq \infty \\ \\ \dfrac{X-Low}{High-Low}, \rho = \infty\end{cases} \tag{5}$$

where

High is the upper limit,
Low is the lower limit, and
ρ is the exponential constant or shape parameter

$$v(X)=\begin{cases}\dfrac{1-e^{\frac{-(High-X)}{\rho}}}{1-e^{\frac{-(High-Low)}{\rho}}}, \rho \neq \infty \\ \\ \dfrac{High-X}{High-Low}, \rho = \infty\end{cases} \tag{6}$$

where

High is the upper limit,
Low is the lower limit, and
ρ is the exponential constant or shape parameter

The exponential constant, ρ, is found using a procedure in which the decision maker defines that score for which the value is exactly midway between the highest value and the lowest value (Kirkwood, 1997). When ρ is positive, the function is concave down. When ρ is negative, the function is concave up. When ρ is infinite, the function is a straight line (Kirkwood, 1997).

3.5.1.2. Qualitative Single-Dimensional Value Functions

Qualitative, or categorical, SDVFs are used when the measure cannot be easily defined by a continuously numerical scale. Examples of occasions when categorical functions are appropriate are when ranking color preferences, retailer preferences, or engine size preferences. Assigning values to each level of the measure can be somewhat arbitrary. One technique for determining values for each level is similar to swing weighting (Kirkwood, 1997) (discussed in 3.6 below). The levels are already ordered from lowest to highest or vice versa. Next, determine the relative value of each successive level as a multiple of the least-valued level. Then, adjust the value of the least-valued level such that the most-valued level has the desired value (usually 1.0). Adjust the values of all the intermediate levels to maintain the same proportions (Kirkwood, 1997). If an alternative includes a level that is not specifically mentioned in the categorical value function, that level is assigned a value of zero.

3.5.2. Single-Dimensional Value Functions for Northern AFB

The following SDVFs were elicited from SMEs at Northern AFB and apply to that base only. Other bases would develop their own SDVFs.

3.5.2.1. SDVF for "Savings Ratio"

Savings Ratio is represented by a continuous, increasing, exponential function. The least preferred level is 1.0, and the most preferred level is 1.2. The mid-value (the level representing the score exactly midway between the highest value and the lowest value (Kirkwood, 1997)) is 1.07, resulting in a concave-down shape. Figure 24 is a diagram of the SDVF for Savings Ratio. Since the least preferred level is 1.0, any

savings ratio equal to or less than breaking even will yield a value of zero. Similarly, any savings ratio equal to or greater than 1.2 will yield a value of one.

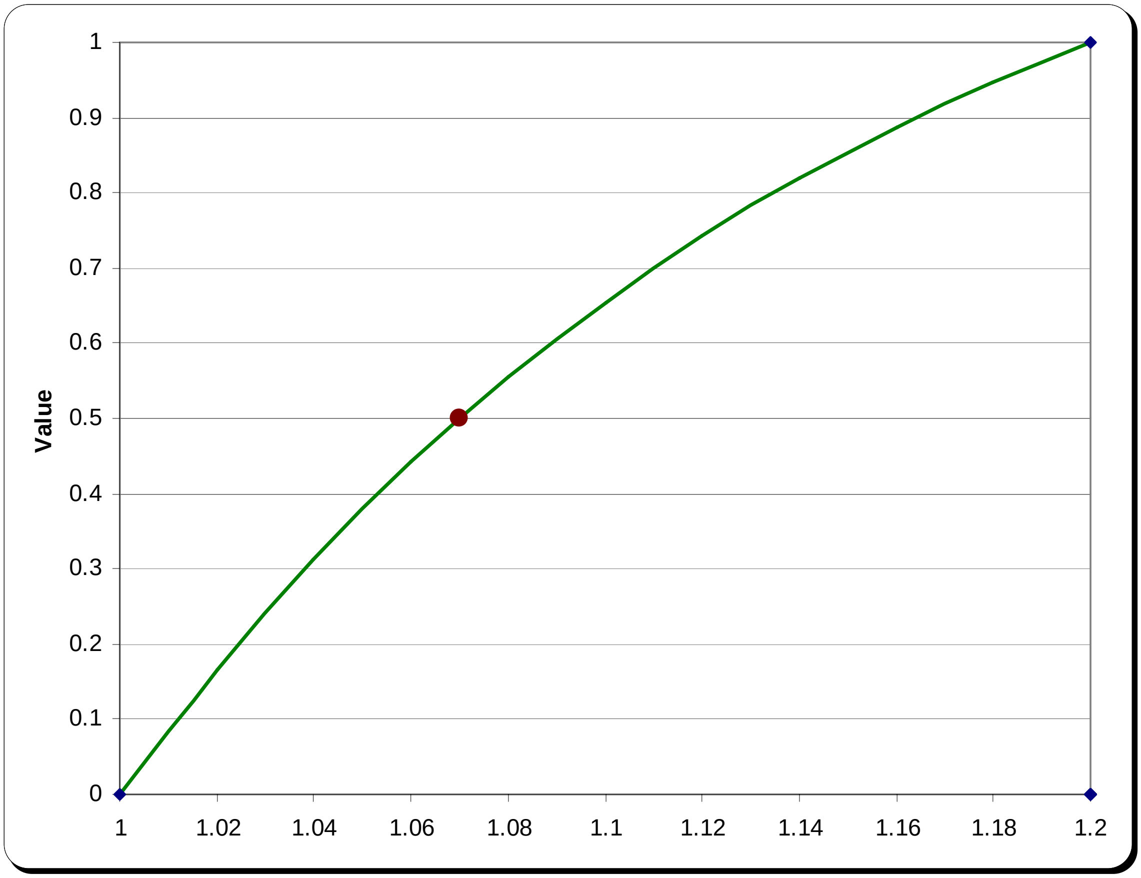


Figure 24: SDVF for Savings Ratio. The SDVF for Savings Ratio is continuous, and increasing from 1.0 to 1.2. The mid-value is at 1.07.

3.5.2.2. SDVF for "Percent Green Electricity"

Percent Green Electricity is represented by a continuous, increasing, exponential function. The least preferred level is zero, and the most preferred level is one. The mid-value is 0.25, resulting in a concave-down shape. Figure 25 is a diagram of the SDVF for Percent Green Electricity. Scores less than zero or more than one are illogical.

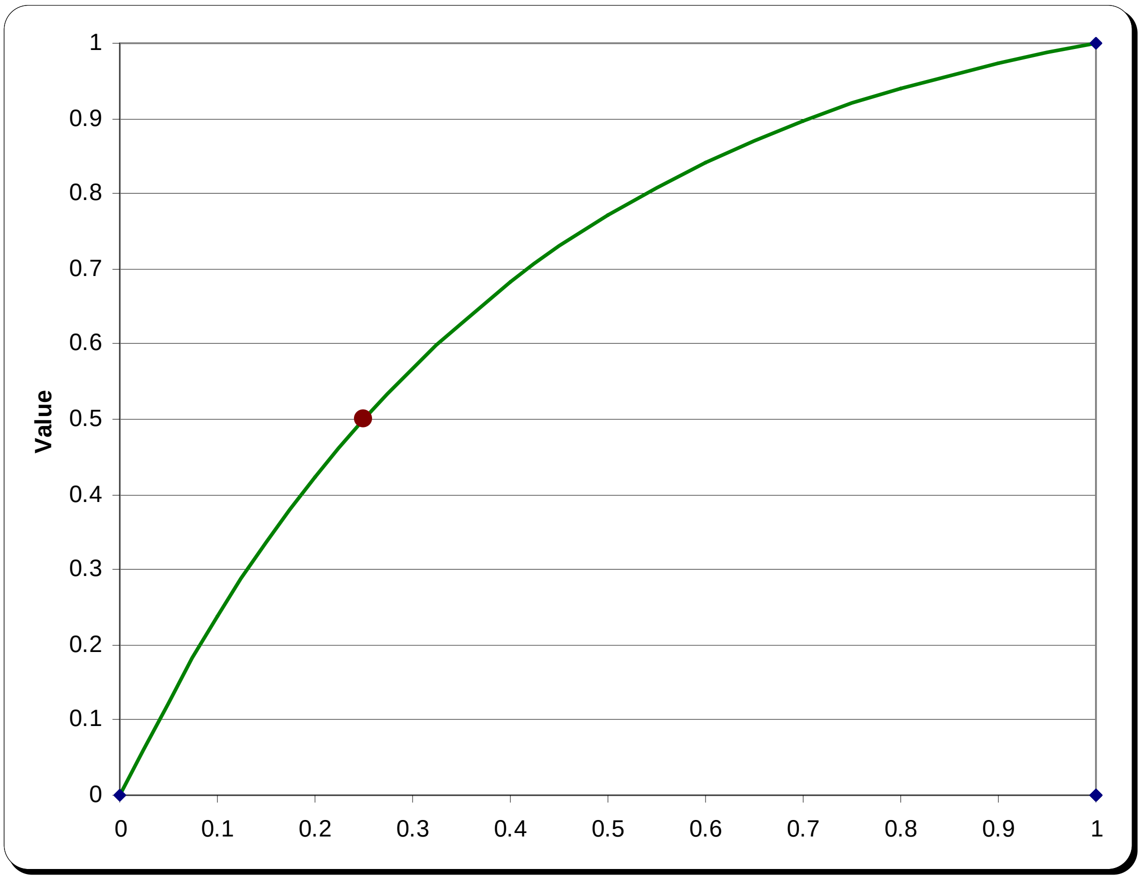


Figure 25: SDVF for Percent Green Electricity. The SDVF for Percent Green Electricity is continuous, and increasing from zero to one. The mid-value is at 0.25

3.5.2.3. SDVF for "Newsworthiness"

Newsworthiness is represented by a categorical function with three levels. An announcement that is not newsworthy (or no announcement at all) receives the lowest

value of zero. If an announcement could likely receive a text-only press release, then it is valued at 0.65. An announcement that also warrants a photo receives the highest value. Figure 26 shows the SDVF for Newsworthiness.

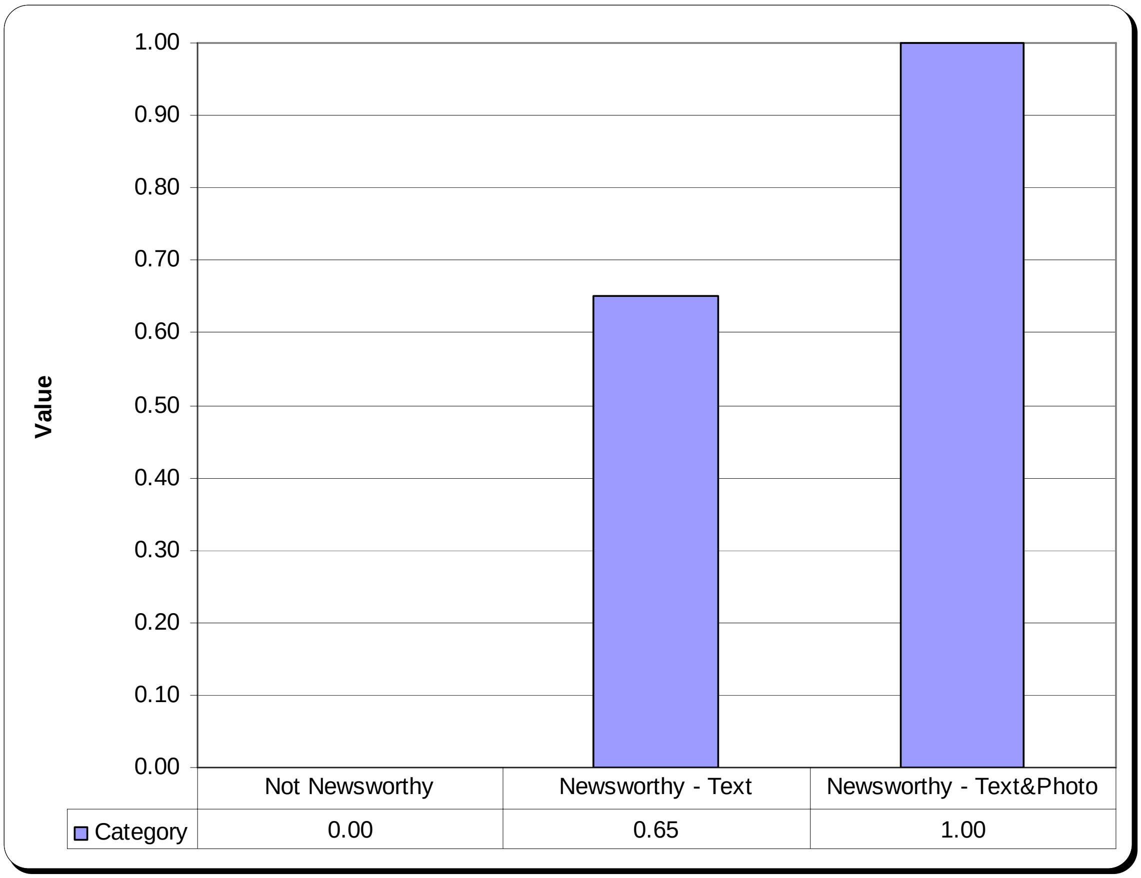


Figure 26: SDVF for Newsworthiness. The SDVF for Newsworthiness is categorical with three levels.

3.5.2.4. SDVF for "NEPA Actions"

NEPA Actions are represented by a categorical function with four levels. If the NEPA process will likely lead to an EIS, which may require approval at the Major Command level, then it will receive a value of 0.10. If an EA FONPA is likely, then the measure will receive a value of 0.40. For an EA FONSI, the resulting value is 0.90. If

the alternative does not require NEPA action or the project will probably qualify for a CATEX, then the value is 1.00. Figure 27 shows the SDVF for NEPA Actions.

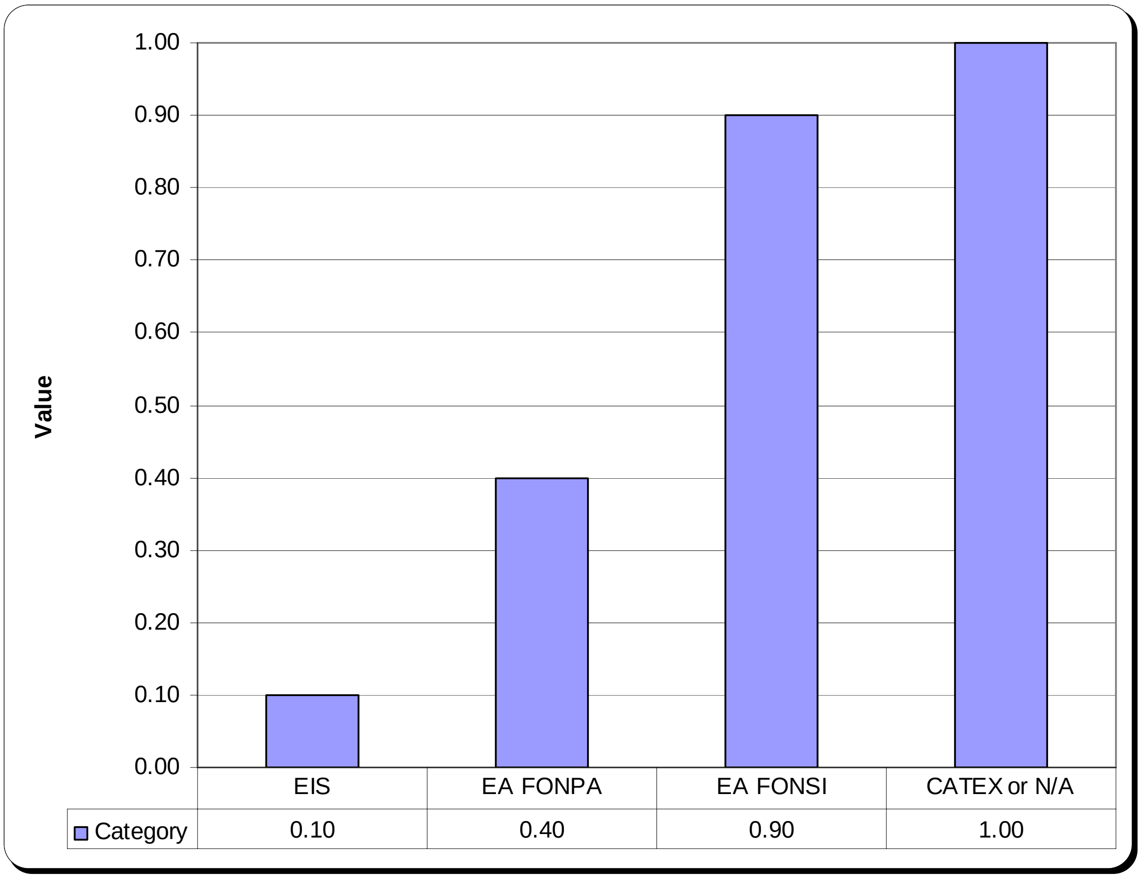


Figure 27: SDVF for NEPA Actions. The SDVF for NEPA Actions is categorical with four levels.

3.5.2.5. SDVF for "Local Suppliers"

Local Suppliers is described as the number of suppliers within a user-defined radius. Northern AFB defined that radius as 500 miles. Local Suppliers is represented by a continuous, increasing, exponential function, though, since fractions of a supplier are not possible, a categorical function would have also worked. The least preferred level of the measure is one supplier, and the most preferred level is six suppliers. The mid-value

is two suppliers, resulting in a concave-down shape. Figure 28 is a diagram of the SDVF for Local Suppliers. Since the least preferred level is one supplier, if the number of suppliers within 500 miles is one or none, the value will be zero. Similarly, six or more suppliers within the radius will yield the maximum value.

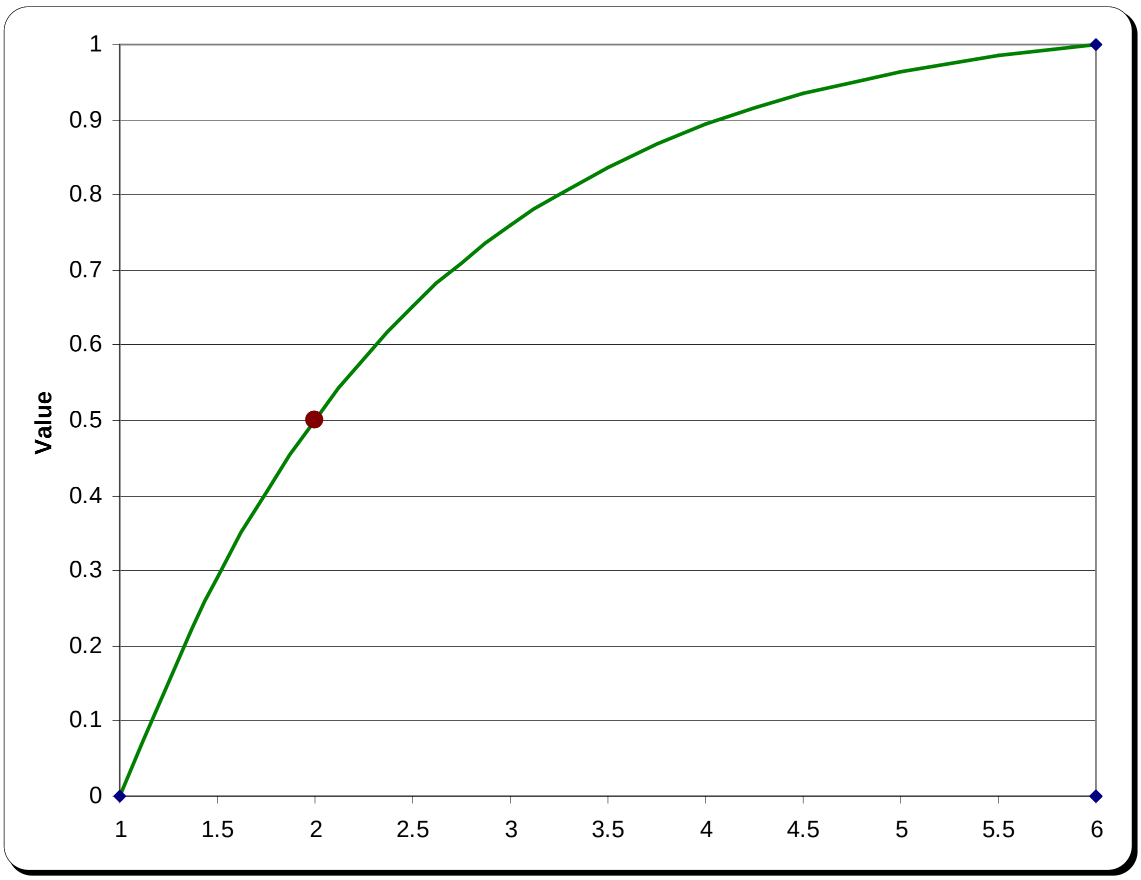


Figure 28: SDVF for Local Suppliers. The SDVF for Local Suppliers is continuous, and increasing from one supplier within 500 miles to six suppliers within 500 miles. The mid-value is two suppliers.

3.5.2.6. SDVF for "Manufacturer Longevity"

Manufacturer Longevity is represented by a continuous, increasing, exponential function. The least preferred level is four years, and the most preferred level is 12 years.

The mid-value is 10 years, resulting in a concave-up shape. Figure 29 is a diagram of the SDVF for Manufacturer Longevity. Since the least preferred level is four years, any manufacturer that has been in business for four years or less will receive a value of zero, while a manufacturer that has been in business for 12 or more years will earn a value of one.

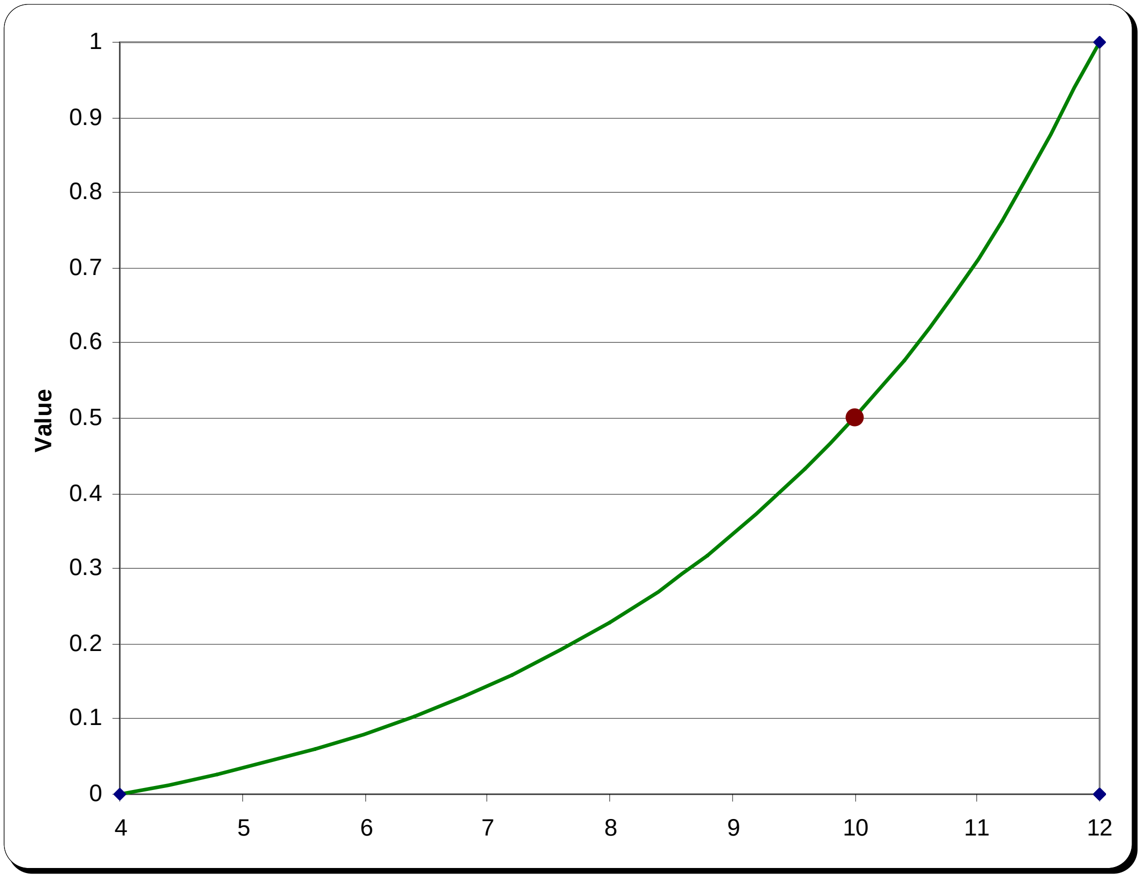


Figure 29: SDVF for Manufacturer Longevity. The SDVF for Manufacturer Longevity is continuous, and increasing from four years to 12 years. The mid-value is at 10 years.

3.5.2.7. SDVF for "Proven Technology"

Proven Technology is represented by a continuous, increasing, exponential function. The least preferred level is 30 system-years, and the most preferred level is 250 system-years. The mid-value is 180 system-years, resulting in a concave-up shape. Figure 30 is a diagram of the SDVF for Proven Technology. Any technology that achieves equal to or less than 30 system-years will receive a value of zero, while a technology that boasts 250 system-years or more will receive the full value.

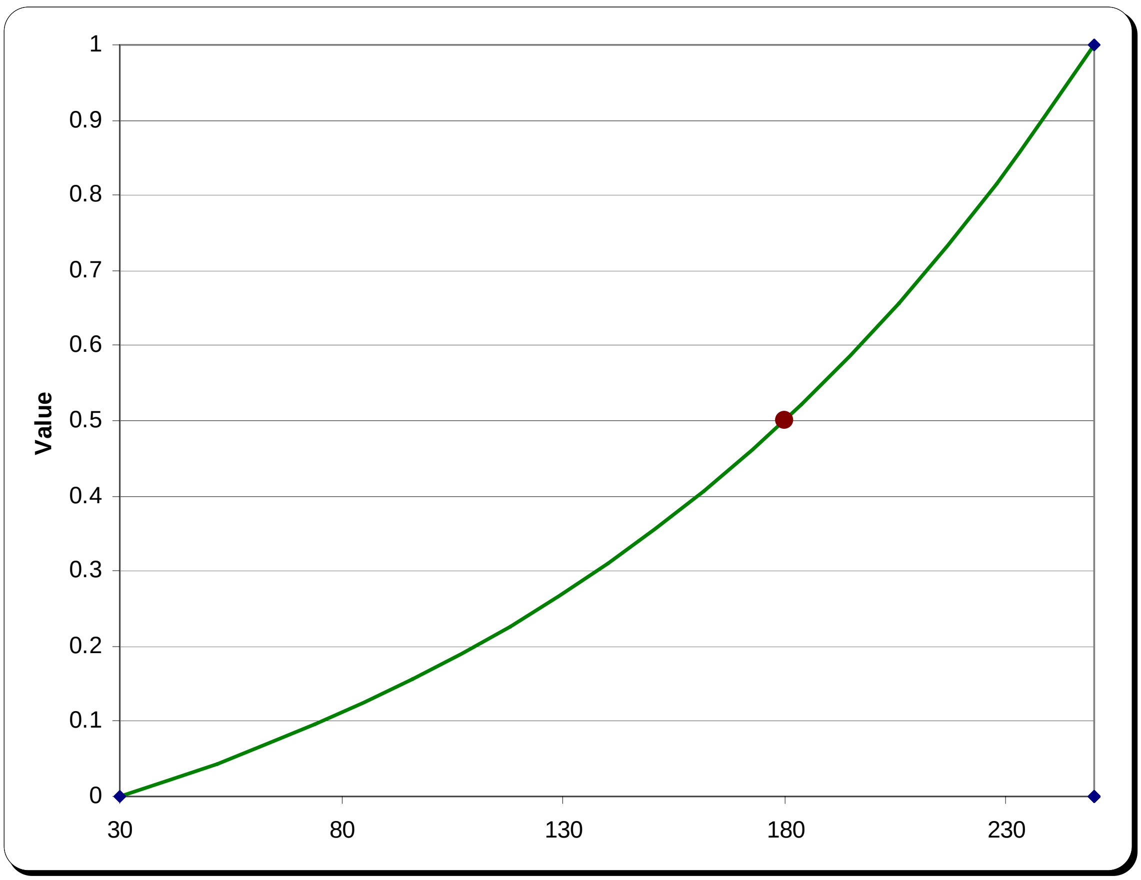


Figure 30: SDVF for Proven Technology. The SDVF for Proven Technology is continuous, and increasing from 30 system-years to 250 system-years. The mid-value is at 180 system-years.

3.5.2.8. SDVF for "Initial Training"

Initial Training is represented by a continuous, decreasing, exponential function. The least preferred level is 160 hours, and the most preferred level is 40 hours. The mid-value is at 120 hours, resulting in a concave-down shape. Figure 31 is a diagram of the SDVF for Initial Training. If initial training were to take 160 hours or more, the alternative will receive a value of zero for this measure. Similarly, if the alternative is projected to require only 40 hours or less of initial training, then it will earn a value of one.

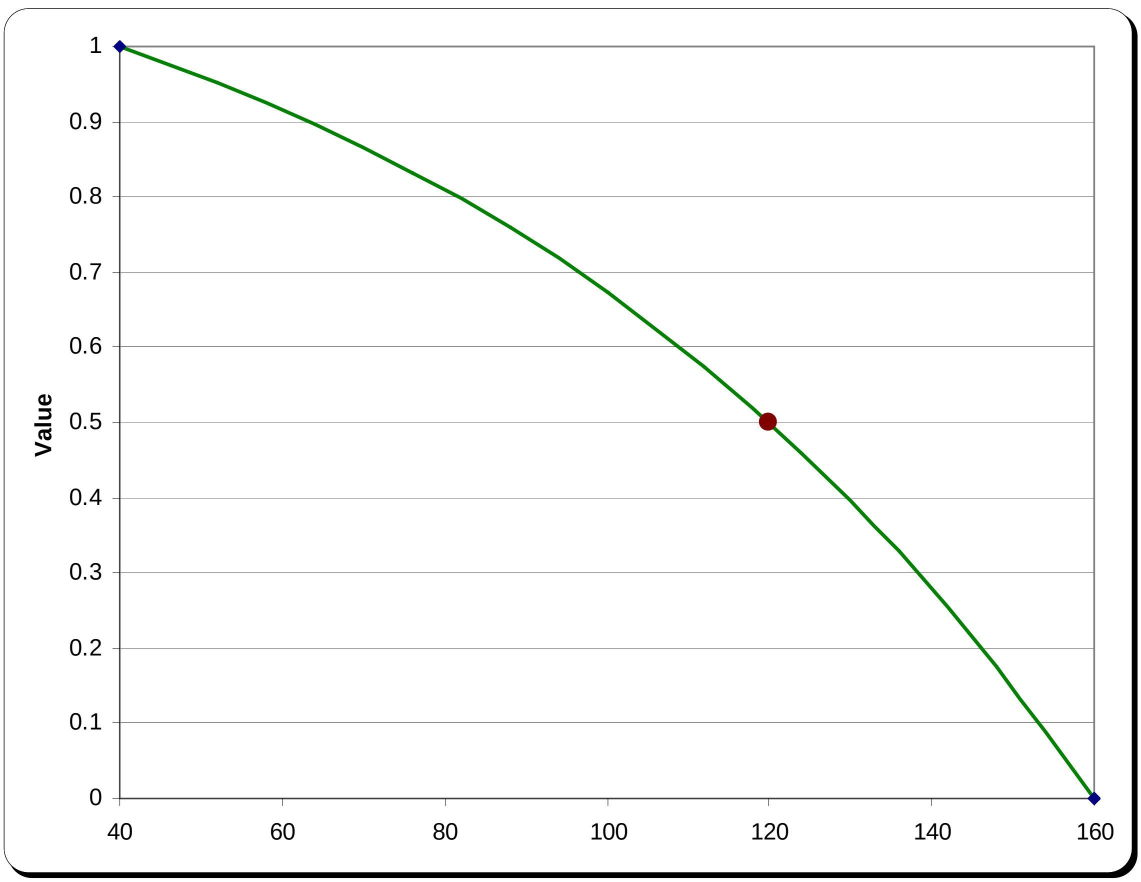


Figure 31: SDVF for Initial Training. The SDVF for Initial Training is continuous, and decreasing from 40 hours to 160 hours. The mid-value is at 120 hours.

3.5.2.9. SDVF for "Intrusivity Level"

Intrusivity Level is represented by a categorical function with six levels. An installed photovoltaic system could cause an *intrusivity* in three basic settings: location on the ground, location in an inhabited area, and location near a flightline. Combinations of these settings can worsen the Intrusivity. The worst-case, receiving a value of 0.15, is if the systems is installed on the ground, in an inhabited area, and near a flightline. One step up, with a value of 0.35, is the same as the previous but in an uninhabited area. One more step up, and earning a value of 0.50, is a system installed on the ground in an inhabited area, but not near a flightline. The next step up, receiving a score of 0.80, is an installation on the ground, but near nothing significant. Also receiving a score of 0.80 is a rooftop system near a flightline. Finally, the only combination that earns the full value is a rooftop system not near a flightline. An alternative to which this measure does not apply will also receive the full value. Figure 32 shows the SDVF for Intrusivity Level.

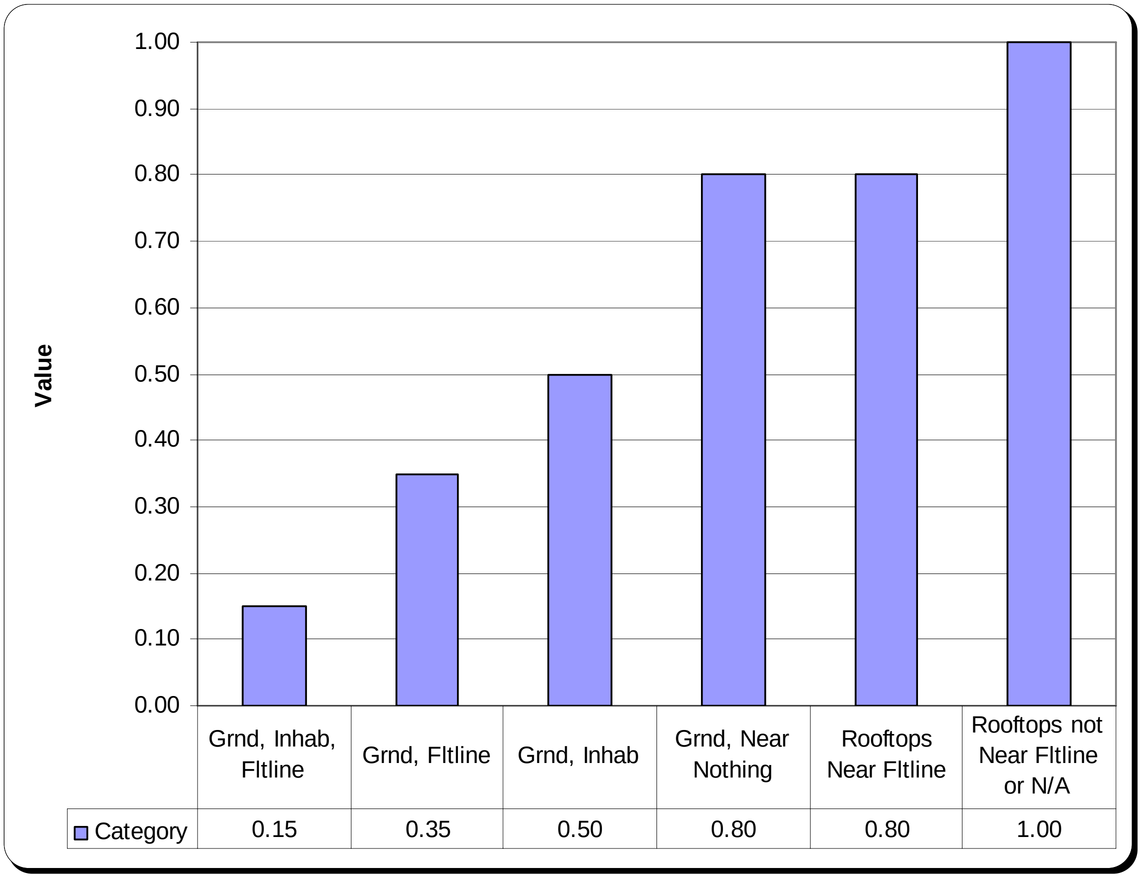


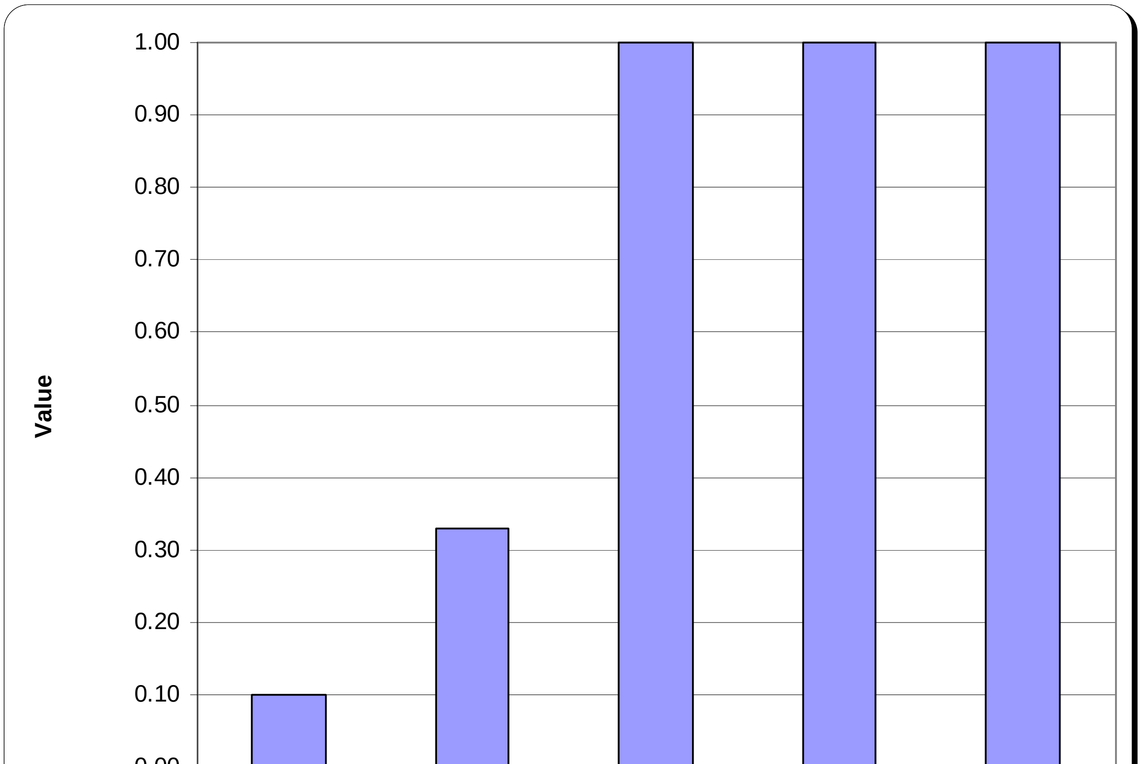
Figure 32: SDVF for Intrusivity Level. The SDVF for Intrusivity Level is categorical with six levels.

3.5.2.10. SDVF for "Own-Operate-Maintain"

Own-Operate-Maintain is represented by a categorical function with five levels. Similar to the last measure, the levels of this measure are combinations of options. In Own-Operate-Maintain, as the name implies, the objective is to decide who will own the system, who will operate the system, and who will maintain the system. The choices are the Air Force, a contractor, and the local utility. The highest risk to the Air Force is if it owns, operates, and maintains a photovoltaic system. Conversely, the lowest risk is if someone else has all of these responsibilities. As expected, the combination earning the lowest value, 0.10, is AF-AF-AF, representing a system that is Air Force-owned,

operated, and maintained, respectively. AF-KTR-KTR gets a value of 0.33. UTIL-KTR-KTR, UTIL-UTIL-UTIL, and KTR-KTR-KTR, each representing the lowest risk to the Air Force, earn the full value.

Figure 33 shows the SDVF for Own-Operate-Maintain.



	AF-AF-AF	AF-KTR-KTR	UTIL-KTR-KTR	UTIL-UTIL-UTIL	KTR-KTR-KTR
Category	0.10	0.33	1.00	1.00	1.00

Figure 33: SDVF for Own-Operate-Maintain. The SDVF for Own-Operate-Maintain is categorical with five levels.

3.6. Step Five: Weight the Objectives Hierarchy

The weight assigned to a particular objective shows its relative importance with respect to other objectives (Kirkwood, 1997). Objectives with a greater weight are more important to the decision maker than lesser-weighted objectives. An easy method for

determining weights is called swing weighting. This process is similar to that referred to in 3.5.1.2 above. First, the objectives are ranked in order of importance from lowest to highest. Second, each objective is evaluated as a multiple of the lowest weighted objective. Third, the weightings are proportionally adjusted such that the sum of all weights equals one (Kirkwood, 1997).

Another simple method for weighting objectives is to suppose with the decision maker that he has 1000 marbles to allocate to each of the objectives (Jeoun, 2005). He must distribute the marbles according to how important he feels each objective is. Thus, the number of marbles allotted to each objective, divided by 10, is the percent of weight assigned to the respective objective (Jeoun, 2005).

The method of weighting used in this research was swing weighting. Northern AFB provided the following relative weights shown in Table 13. The measures are only weighted against each other within their respective branch.

Table 11: Relative Value and Measure Weights at Northern AFB

Economic Value	1.50	Savings Ratio	1.00
Environmental Value	1.00	Percent Green Electricity	3.60
		Newsworthiness	1.00
		NEPA Actions	3.00
Operation Value	1.33	Local Suppliers	1.10
		Manufacturer Longevity	1.00
		Proven Technology	1.20
		Initial Training	1.00
		Intrusivity Level	1.33
		Own-Operate-Maintain	1.50

The final global weights of all measures are shown in Table 12.

Table 12: Global Measure Weights at Northern AFB

Savings Ratio	0.392
Percent Green Electricity	0.124
Newsworthiness	0.034
NEPA Actions	0.103
Local Suppliers	0.062
Manufacturer Longevity	0.032
Proven Technology	0.038
Initial Training	0.056
Intrusivity Level	0.075
Own-Operate-Maintain	0.084

Savings Ratio carries the bulk of the weight with over one third of the influence. It is also important to note that the three greatest-weighted measures (Savings Ratio, Percent Green Electricity, and NEPA Actions) carry about 62 percent of the total weight, while the five least-weighted measures (Local Suppliers, Initial Training, Proven Technology, Newsworthiness, and Manufacturer Longevity) hold only 22 percent of the total weight.

3.7. Step Six: Generate Alternatives

The *generation* of alternatives is one of the advantages of VFT. Since the decision maker's objectives were stated up front in Step Two before having much knowledge of the available alternatives, new alternatives that generally meet the objectives can be created and combined with the available alternatives. It is conceivable that the newly-generated alternatives will be of higher quality and possess more desirable characteristics than the available alternatives.

3.7.1. Strategy Table Background

Creating alternatives, however, can result in far too many choices than can be practically evaluated. Consider a VFT model that has five evaluation measures. If each evaluation measure has even two levels, then the analyst will have 2^5, or 32, potential new alternatives to score, requiring considerable time and resources. As the number of measures and levels increases, the burden surges. In circumstances when the number of generated alternatives is greater than is practical, the strategy table is a useful tool for quickly eliminating alternatives that are undesirable or illogical. Howard gives the example of a restaurant that claims its burgers, having 10 ingredients, are so customizable that 1024 different possibilities exist (Howard, 1988). What they fail to mention is that one combination is the "nullburger," while another combination is simply the lettuce by itself, and another might be simply pickles and cheese (Howard, 1988). Would a customer really pay for these choices? These "alternatives" are hardly worthy of consideration. A strategy table would have helped the restaurant owners eliminate those combinations that make little sense and focus more on those that do make sense, like a burger that actually has a bun and some substance. The strategy table breaks each characteristic into several levels. Using the burger example, the characteristics are the 'ingredients'; the levels are 'having' or 'not having' the particular ingredient. Then, to generate each alternative, one single level of each characteristic is chosen. In actuality, not all characteristics need to be defined for every alternative, only those that help create interesting and applicable alternatives.

3.7.2. Strategy Table Alternatives for Northern AFB

For this photovoltaic decision model, five characteristics were chosen to make up the strategy table. They are System Placement, Module Technology, Intrusivity, NEPA Actions, and Operation Risk. Table 13 breaks down the characteristic levels.

Table 13: Strategy Table Characteristic Levels and Combinations

System Placement	*Module Technology*	*Intrusivity*	*NEPA Actions*	*Operation Risk*
4 Small Admin Roofs	c-Si	Grnd, Inhab, Fltline	EIS	AF-AF-AF
1 Large Admin Roof	a-Si	Grnd, Inhab	EA FONPA	AF-KTR-KTR
Shaded Parking	CdTe			
Hangar Roof	CIGS			
Field Array				

The assumptions associated with System Placement will be discussed in Chapter 4. Where actual measures were chosen as the characteristics that make up the strategy table, the careful observer will notice that not all levels of the measure are shown. Those levels that are present represent the worst-case level or significant breakpoints within the measure's range. The philosophy behind this method is the following. Utilizing all levels of the measure will generate many more alternatives than can be feasibly evaluated. The purpose of the strategy table is to reduce the number of alternatives that will be evaluated. If a particular alternative performs reasonably well given the limited levels available, then a further analysis can be undertaken to provide more detail. Also, if an alternative still competes effectively against the *status quo* at these lesser-valued levels, then another similar alternative with better characteristics should perform even better in a more in-depth analysis.

The strategy table revealed 57 logical combinations, which are shown in Appendix A. These 57 alternatives will stress the model since the scores for the three measures

used in the strategy table are sub-optimal. However, in order to evaluate photovoltaic's potential under optimum conditions, two additional alternatives will also be added. They are numbered 58 and 59, and they assume minimal intrusivity, a categorical exclusion under NEPA, and minimum operational risk. Further analysis will be performed on all 13 alternatives, which were selected for their competitive ranking (shown in Appendix B), their diversity of characteristics, and their optimality as discussed. The 13 alternatives are shown in Table 14.

Table 14: Selected Alternatives for Further Analysis

Alternative Name	*Intrusivity Level*	*NEPA Actions*	*Own-Operate-MX*
01 - Four Small Admin Roofs, a-Si Rolls	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
02 - Four Small Admin Roofs, CdTe	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
07 - Large Admin Roof, CIGS	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
08 - Large Admin Roof, c-Si	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
16 - Parking Shade, CIGS	Rooftops not Near Flightline or N/A	EA FONPA	AF-KTR-KTR
20 - Parking Shade, c-Si	Rooftops not Near Flightline or N/A	EA FONPA	AF-KTR-KTR
24 - Hangar Roof, CdTe	Rooftops Near Flightline	EA FONPA	AF-KTR-KTR
32 - Hangar Roof, c-Si	Rooftops Near Flightline	EA FONPA	AF-KTR-KTR
48 - Field Array, CdTe	Grnd, Inhabited Area	EA FONPA	AF-KTR-KTR
56 - Field Array, c-Si	Grnd, Inhabited Area	EA FONPA	AF-KTR-KTR
57 - Do Nothing	Rooftops not Near Flightline or N/A	CATEX or N/A	UTIL-UTIL-UTIL
58 - Field Array, c-Si	Grnd, Near Nothing	CATEX or N/A	UTIL-UTIL-UTIL
59 - Parking Shade, c-Si	Rooftops not Near Flightline or N/A	CATEX or N/A	UTIL-UTIL-UTIL

Having fully constructed the model and generated alternatives, the next chapter continues Shoviak's 10-step process by scoring the alternatives and performing deterministic and sensitivity analyses.

4. Analysis

4.1. Introduction

This chapter covers the next three steps in Shoviak's 10-step process. The alternatives will be scored and ranked using the SDVFs and weightings. A sensitivity analysis will also be completed to determine the ranking impact of changing selected assumptions.

4.2. Step Seven: Score the Alternatives

Now that the alternatives have been generated in Step Six, the measures must be assessed for each alternative. This produces a matrix of raw alternative-measure scores. These entries are not necessarily the same for any base using the model since some measures are location-specific, such as Savings Ratio, which incorporates geographical solar radiation data, local electricity costs, and location cost factors for construction. Once raw scores were established, final values were obtained as discussed in their respective sections in 3.4 and 3.5.2 above.

4.2.1. Raw Alternative Scores for Northern AFB

The raw scores for the 13 alternatives are shown in Table 15. As discussed in Chapter 3, Savings Ratio is the dimensionless ratio of all benefits to all costs over the systems lifespan; Percent Green Electricity is the total level of green electricity consumed at the base; Newsworthiness is a measure of the public relations benefit realized after installing a photovoltaic system; NEPA Actions are the anticipated outcome of the NEPA process; Local Suppliers is a measure of how many component suppliers are within a defined radius of the base; Manufacturer Longevity is the length of time that the

manufacturer has been in business; Proven Technology is the sum of the products of the number of systems with a particular module type and the number of years that system has been in operation; Initial Training is the number of hours of training to advance novice workers to technicians who are comfortable with the system; Intrusivity Level is a measure of the effect on available real estate, local inhabited areas, and flightline operations; and Own-Operate-Maintain is a measure of the level of risk assumed by the Air Force from owning, operating, or maintaining a photovoltaic system.

Table 15: Raw Alternative-Measure Scores

Alternative Name	*Savings Ratio*	*Percent Green Electr*	*News-worthiness*	*NEPA Actions*	*Local Suppliers*	*Manuf Longevity*	*Proven Tech*	*Initial Training*	*Intrusivity Level*	*Own-Operate-MX*
01 - Four Small Admin Roofs, a-Si Rolls	0.27	17.62%	Newsworthy - Text	CATEX or N/A	5	unk	1000	40	Rooftops Not Near Fltline or N/A	AF-AF-AF
02 - Four Small Admin Roofs, CdTe	0.24	17.64%	Newsworthy - Text	CATEX or N/A	4	3	240	40	Rooftops Not Near Fltline or N/A	AF-AF-AF
07 - Large Admin Roof, CIGS	0.20	17.69%	Newsworthy - Text	CATEX or N/A	4	7	210	40	Rooftops Not Near Fltline or N/A	AF-AF-AF
08 - Large Admin Roof, c-Si	0.23	17.75%	Newsworthy - Text	CATEX or N/A	6	18	1000	40	Rooftops Not Near Fltline or N/A	AF-AF-AF
16 - Parking Shade, CIGS	0.12	17.72%	Newsworthy - Text&Photo	EA FONPA	4	7	210	40	Rooftops Not Near Fltline or N/A	AF-KTR-KTR
20 - Parking Shade, c-Si	0.15	17.80%	Newsworthy - Text&Photo	EA FONPA	6	18	1000	40	Rooftops Not Near Fltline or N/A	AF-KTR-KTR
24 - Hangar Roof, CdTe	0.23	17.85%	Newsworthy - Text&Photo	EA FONPA	4	3	240	40	Rooftops Near Fltline	AF-KTR-KTR
32 - Hangar Roof, c-Si	0.22	18.08%	Newsworthy - Text&Photo	EA FONPA	6	18	1000	40	Rooftops Near Fltline	AF-KTR-KTR
48 - Field Array, CdTe	0.24	18.14%	Newsworthy - Text&Photo	EA FONPA	4	3	240	80	Grnd, Inhab	AF-KTR-KTR
56 - Field Array, c-Si	0.23	18.63%	Newsworthy - Text&Photo	EA FONPA	6	18	1000	80	Grnd, Inhab	AF-KTR-KTR
57 - Do Nothing	1.00	17.58%	Not Newsworthy	CATEX or N/A	6	1000	1000	0	Rooftops Not Near Fltline or N/A	UTIL-UTIL-UTIL
58 - Field Array, c-Si	0.23	18.63%	Newsworthy - Text&Photo	CATEX or N/A	6	18	1000	80	Grnd, Near Nothing	UTIL-UTIL-UTIL
59 - Parking Shade, c-Si	0.15	17.80%	Newsworthy - Text&Photo	CATEX or N/A	6	18	1000	40	Rooftops Not Near Fltline or N/A	UTIL-UTIL-UTIL

4.2.2. Alternative-Measure Assumptions

Several assumptions were made to complete this analysis. First, all buildings are assumed to be "ideal," meaning, rooflines are perfectly east-west permitting a southern exposure for photovoltaic systems; when a roof is sloped, it is sloped at an angle practical

for construction, but very close to latitude; flat roofs have modules on frames tilted at an angle equal to latitude, except the parking shade which is assumed to have modules lying horizontal; the hangar roof is assumed to be semi-cylindrical, and the module tilt is approximated by dividing the rated system output by three and evaluating one third at a tilt of 23^{o}, one third at a tilt of 45^{o}, and one third at a tilt of 67^{o}; all roofs can support the distributed weight of the systems being evaluated; and all rooftop arrays are in locations free from shadows. Likewise, field arrays are located in an ideal manner with optimum solar exposure. Modules used in the alternatives are shown in Table 16. No endorsement is implied.

Table 16: Modules Used in the Analysis

Module Technology	*Manufacturer*	*Model*
c-Si	SunPower	SPR-210
a-Si	Uni-Solar	PVL-136
CdTe	First Solar	FS-65
CIGS	Würth Solar	WS 31050/80

Assumptions and calculations leading to raw scores for Savings Ratio and Percent Green Energy are shown in Appendix C. Scores for Newsworthiness were based on a judgment of what type of press release a particular alternative could generate. Photovoltaic systems installed on administrative building roofs were determined not to provide a good photo opportunity. Scores for NEPA Actions were based upon educated speculation of what type of action the installation of an alternative would trigger, but they also derive from the strategy table. Scores for Local Suppliers were originally pursued as outlined in Appendix E; however, the radius was set so high (500 miles) that every alternative received the maximum value. One neighboring state alone had over 30 suppliers that fell within the radius. To make the model more interesting, each alternative

had the number of suppliers randomly assigned within the range of the SDVF. Scores for Manufacturer Longevity were determined based on information found on company websites. The link to the applicable data on one company's website was broken and company representatives failed to respond to inquiries, resulting in the "unknown" score. Scores for Proven Technology were very difficult to ascertain. Given more time and resources, data available from several sources could be scoured to develop an approximate answer; however, most announcements, discussions, or listings of photovoltaic systems failed to provide enough data to make an accurate determination. Therefore, scores were determined based on how long particular technologies have been in commercial production. Scores for Initial Training were founded upon the perceived complexity that a system might convey. More complex systems will demand more time and training to get novice technicians over their fears. As such, field arrays were judged to be perceived as more complex than the other systems. Scores for Intrusivity Level are based on the system placement in Table 13 and come from the strategy table. Finally, Own-Operate-Maintain scores originate directly from the strategy table.

4.3. Step Eight: Perform Deterministic Analysis

Equation 1 in 2.3.2.3 above shows the Multiobjective Value Function. The equation refers to $v(X_1, X_2, X_3,\ldots, X_i)$ as an alternative's value given the weightings and the alternative's raw scores. This calculation of the additive value function is performed for each alternative in Step Eight using a Microsoft Excel add-in developed at the Air Force Institute of Technology (Weir, 2006). Then, the values for all alternatives are rank-ordered to reveal the preference structure. Figure 34 is the result of this analysis. Longer bars represent greater value, and thus, higher preference.

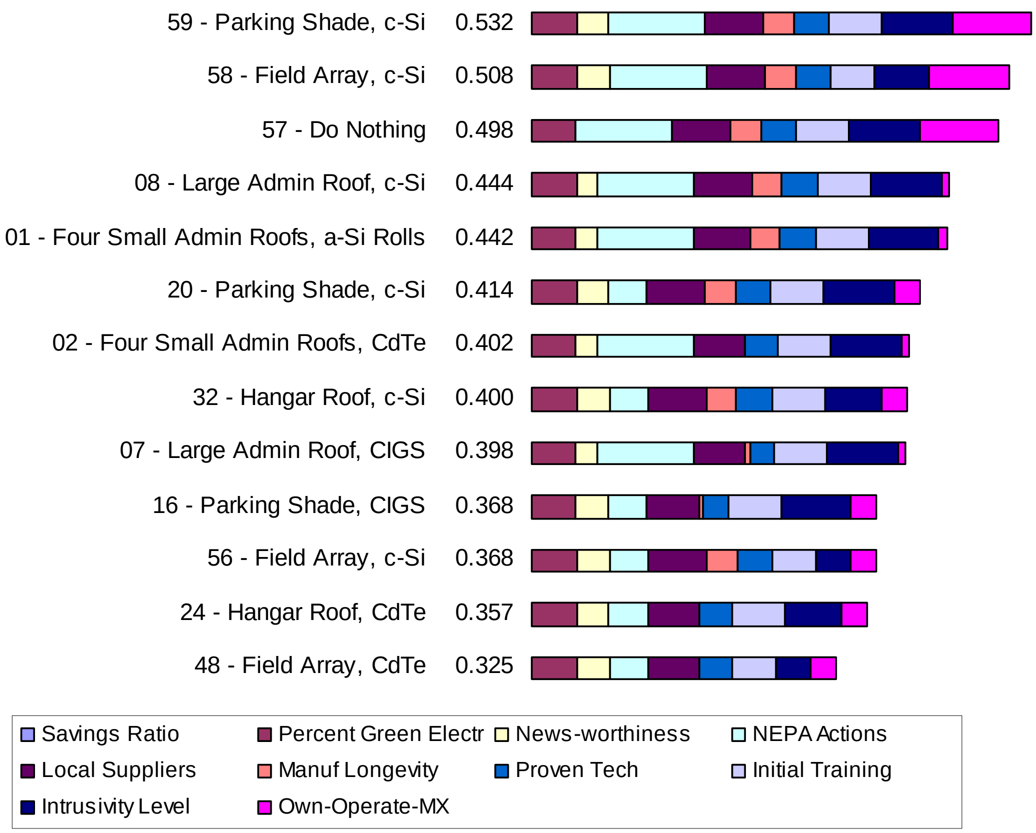


Figure 34: Ranking of Selected Alternatives. The rank-ordering of the selected alternatives reveals which ones are most preferred.

Looking at Figure 34, much can be learned. First, none of the alternatives achieves any value for Savings Ratio. This is because the Savings Ratio is not greater than 1.0 for any alternative, including the "do nothing" alternative. The measure of Percent Green Electricity has minimal effect on the rank ordering since the variation ranges only between 17.6 percent and 18.6 percent. This minimal variation is because Northern AFB consumes so much electricity that installing photovoltaic systems of the capacities shown in Appendix C have only small effects on the amount of electricity purchased off the grid. If the slope of the SDVF for Percent Green Energy were steeper in this range, then this measure would have a greater effect on the final value. Newsworthiness is one measure

for which all alternatives earn value, except the “do nothing” alternative, as continuing the *status quo* is not particularly newsworthy. Most of the alternatives that ranked highly earned much of there value from NEPA Actions. This can be reasonably expected since installing a green energy source that has detrimental effects on the environment is counter-intuitive. Local Suppliers has an overall minimal effect on the final rankings since it is weighted low, and the scores for the alternatives lie in that portion of the SDVF where the slope is fairly flat. Manufacturer Longevity generally contributes less to total value than some other measures due to its low weight; however, it does have greater variation, so therefore, acts as an effective discriminator. Proven Technology and Initial Training are two more measures with relatively low weight (together, they account for less than 10 percent of the total weight), and, like Local Suppliers, there variation is low, so their effectiveness as discriminators is reduced, except to differentiate between two alternatives for which all the other measures are equal. Intrusivity Level showed moderate variation and it has greater weight than five of the ten measures. Those alternatives that ranked higher also scored well with Intrusivity Level.

The measure that is the greatest hurdle to high ranking and which causes all of the alternatives (except the optimized alternatives) to underperform the “do nothing” alternative is Operation Risk. Since the “do nothing” alternative is the same as continuing to purchase electricity from the grid, which the utility owns, operates, and maintains, there is virtually no risk to the Air Force with this alternative. In every other alternative (except the optimized alternatives), the Air Force assumes some amount of risk. In the case of the optimized alternatives, however, the utility company owns, operates, and maintains the photovoltaic system, and thus there is no risk to the Air

Force. The optimized alternatives are the only alternatives that outrank the "do nothing" alternative in the deterministic analysis. The sensitivity analysis in Step Nine will reveal if changing assumptions has an effect on alternative rankings.

4.4. Step Nine: Perform Sensitivity Analysis

The sensitivity analysis is an important tool to gain a better understanding of interactions within the model. A sensitivity analysis can be performed on the weights of values and measures as well as on the SDVF.

4.4.1. Sensitivity Analysis on the Hierarchy Weights

A sensitivity analysis is most commonly performed on the weights of the measures. This is helpful to see if the overall rankings change if the weights are adjusted. In this method of sensitivity analysis, one value's weight is varied from zero to one while the other values' weights are adjusted proportionally.

Figure 35 shows the result of varying the weight of Economic Value while holding the weights of Environmental Value and Operation Value in proportion. The vertical line in Figure 35 is the current location of the weight on Economic Value. As can be seen, at no point does the ranking change. This is because the only measure of Economic Value is the Savings Ratio, and that is zero for all alternatives. Therefore, Economic Value is insensitive to changes in weight.

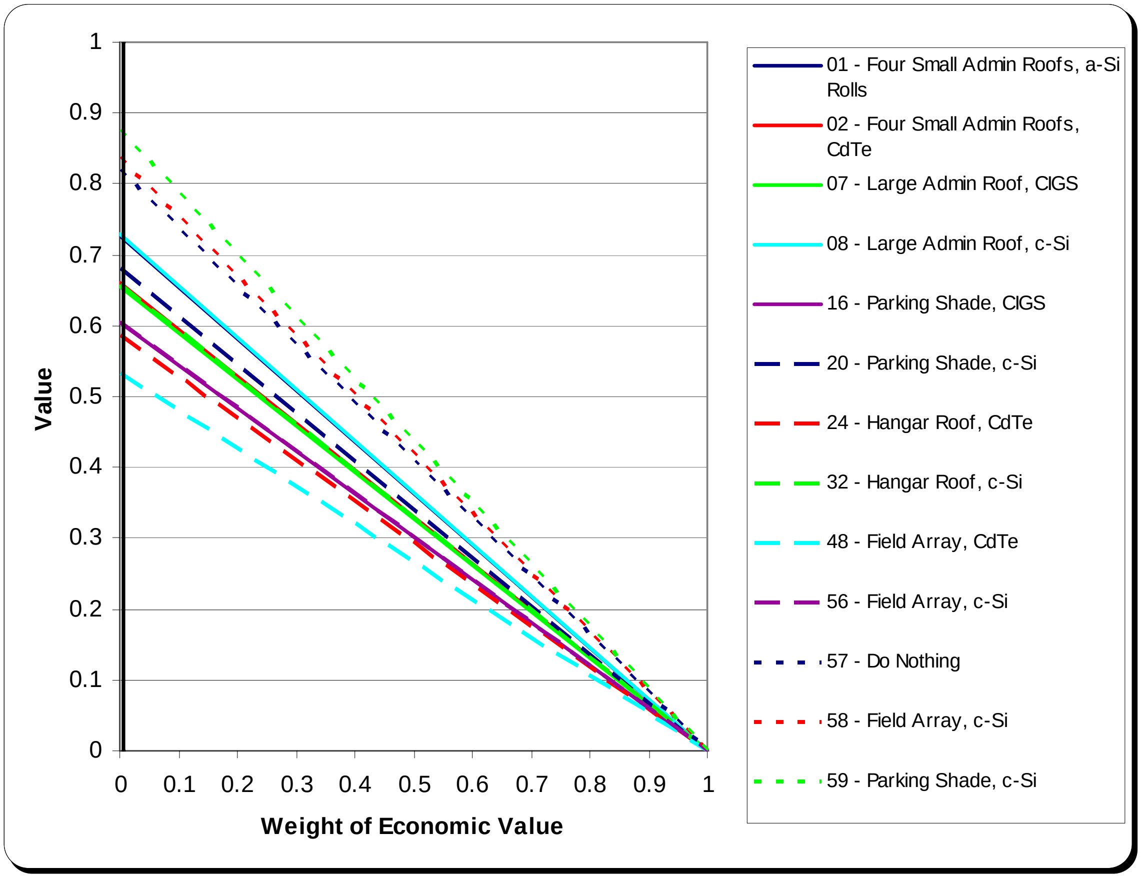


Figure 35: Sensitivity Analysis on Economic Value Weight. A sensitivity analysis on the weight of Economic Value shows no change in ranking. The black line represents the current weight on Economic Value.

Figure 36 represents a sensitivity analysis on the weight of Environmental Value. This analysis is a little more interesting since the alternative ranking changes as the weight of Environmental Value is varied. However, in order to get to a breakpoint at which the "do nothing" alternative ranks lower than the non-optimized alternatives, the weight must change significantly from just over 0.25 to approximately 0.55. Since Environmental Value was the lowest-ranked value of the three first-tier values, it would be difficult to justify such a large weight increase. Therefore, Environmental Value may be considered insensitive to changes in weight over a reasonable range.

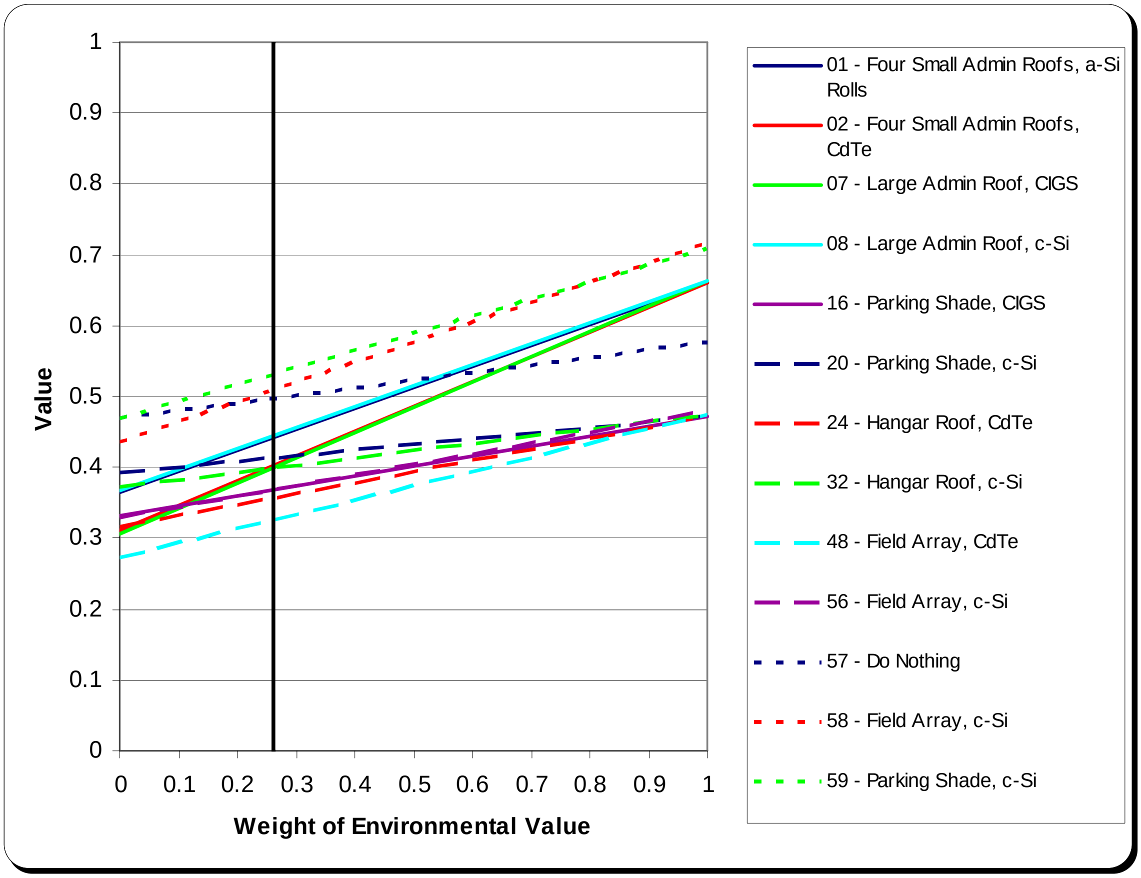


Figure 36: Sensitivity Analysis on Environmental Value Weight. A sensitivity analysis on the weight of Environmental Value shows several changes in ranking. The black line represents the current weight on Environmental Value.

Figure 37 is a sensitivity analysis on the Operation Value weight. Again, the analysis reveals several areas where the ranking changes. Yet, once again, the breakpoint to remove the "do nothing" alternative from its higher position relative to the non-optimized alternatives is close to 0.15. Currently Operation Value holds just over one third of the entire model's weight, so this would be a significant decrease and would be difficult to rationalize. Therefore, Operation Value may be considered insensitive to weight changes within a reasonable range.

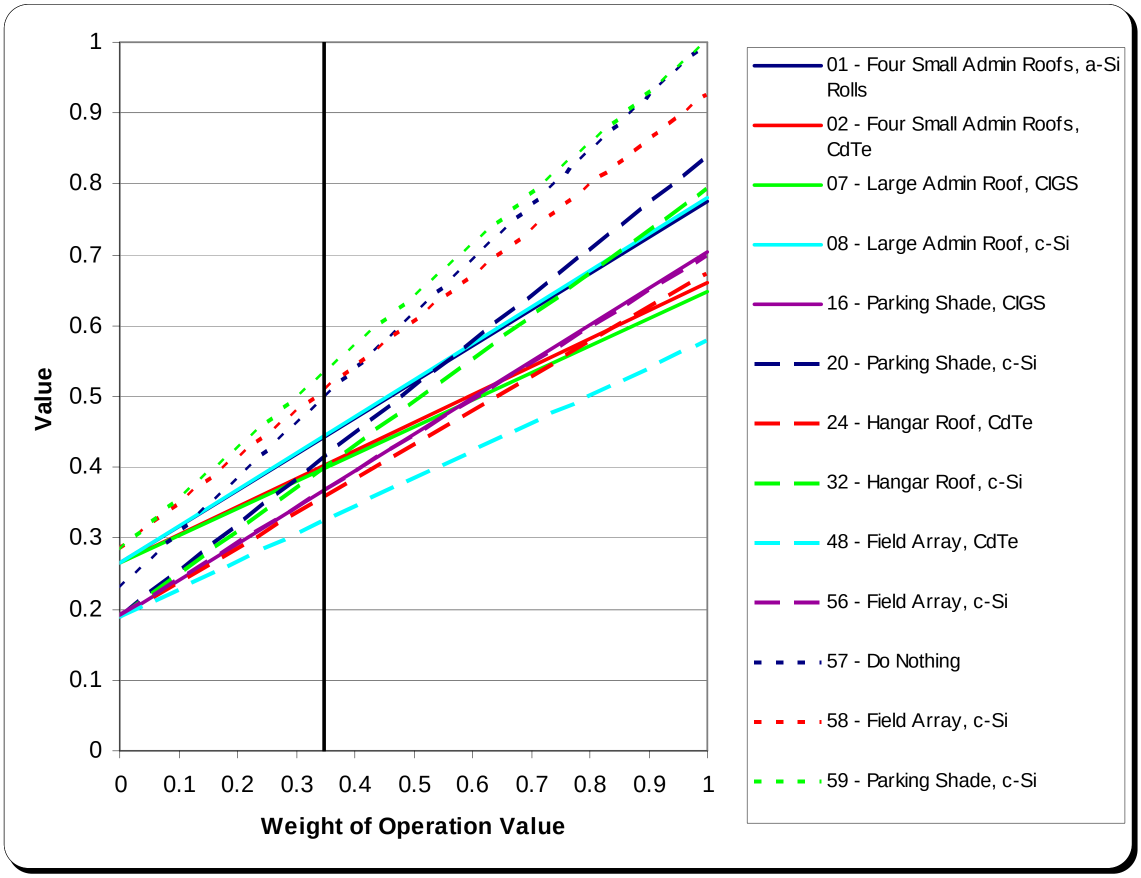


Figure 37: Sensitivity Analysis on Operation Value Weight. A sensitivity analysis on the weight of Operation Value shows several changes in ranking. The black line represents the current weight on Operation Value.

With all three weight-changing sensitivity analyses, the optimized alternatives strongly resisted displacement by the "do nothing" alternative.

Since these three sensitivity analyses show no rank changes with reasonable weight variations, it is unnecessary to conduct more in depth analysis of the weights on second-tier values. Instead, a sensitivity analysis on the SDVFs will be completed.

4.4.2. Sensitivity Analysis on Selected Single-Dimensional Value Functions

A less commonly performed sensitivity analysis is one in which the SDVFs are themselves changed. This evaluation is not as common since it often has little effect on

the final ranking (Kirkwood, 1997). However, that is not the case in this model. All of the assumption changes that will be presented in this section affect the Savings Ratio in some way, and any change that causes the Savings Ratio to be non-zero will have a profound effect of the final alternative ranking.

The first assumption change involves the cost of electricity as reported by one of Northern AFB's SMEs. A testament to the negotiating skill of its energy manager and others, Northern AFB enjoys a very low electricity cost. The average cost paid in 2005 was $0.023 / kWh. For comparison, the US all-sector (residential, commercial, industrial, and transportation) average for 2005 (in 2004 dollars) was $0.083 / kWh (USDOE Energy Information Administration, 2006). The base's fantastic rate is good news for Northern AFB, but it is bad news when making the case for photovoltaics on the base. It becomes very difficult for the other, non-optimized alternatives to perform better than the "do nothing" alternative, especially since Savings Ratio is weighted so heavily. A sensitivity analysis in which the current cost of electricity is increased reveals the result in Figure 38. At around $0.08 / kWh, a non-optimized alternative becomes the highest ranked alternative (with the exception of the optimized alternatives), outranking the "do nothing" alternative, and around $0.10 / kWh, the "do nothing" alternative becomes one of the least preferred alternatives. The solid black line indicates Northern AFB's current (2005) electricity rate ($0.023 / kWh). The dashed black line ($0.08 / kWh) is the rate at which several following analyses are performed. The dotted black line represents the rate at which an alternate deterministic analysis was performed (shown in Figure 39) to demonstrate the profound effect of a higher initial cost of electricity.

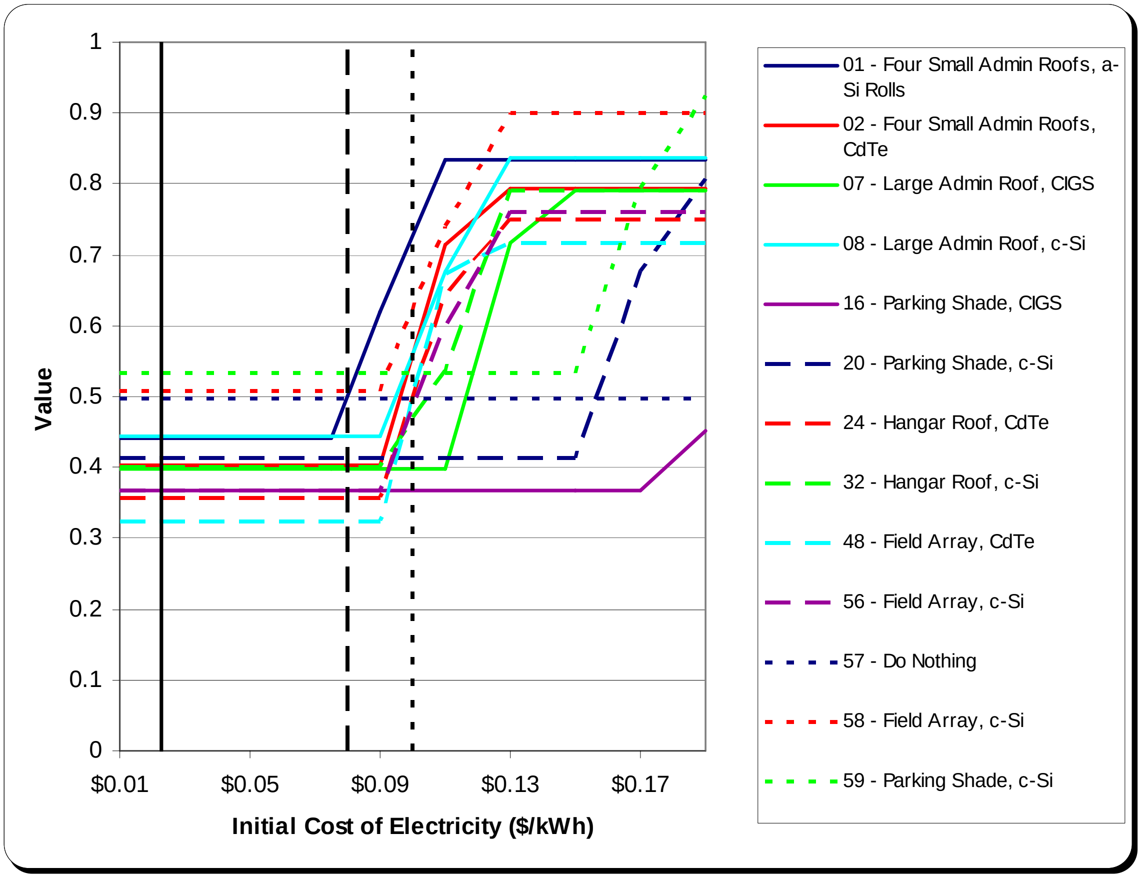


Figure 38: Sensitivity Analysis on Initial Cost of Electricity. A sensitivity analysis on the cost of electricity shows drastic changes in alternative ranks. The solid black line represents Northern AFB's current rate. The dashed black line represents the rate used in several following analyses. The dotted black line represents the rate used in an alternate deterministic analysis shown in Figure 39.

An alternate deterministic analysis was executed using an initial cost of electricity of $0.10 / kWh rather than the actual rate of $0.023 / kWh. In this analysis, a non-optimized alternative (Alternative 01) achieves a significant advantage over the "do nothing" alternative. This analysis shows the intense effect that the initial cost of electricity has on the rankings.

Figure 39: Ranking of Selected Alternatives with Cost of Electricity at $0.10 / kWh. This ranking was performed with the initial cost of electricity set at $0.10 / kWh to show the strong effect that the cost of electricity purchased from the grid has on the final ranking. Compare this with Figure 34, which used $0.023 / kWh to perform the same analysis.

Another analysis evaluates the change in electricity cost inflation to see if the ranking order changes when the rate of increase of electricity cost is greater than the rate of increase of maintenance cost. Electricity cost inflation is the basically the inflation rate used in Equation 4 (Future Value calculation) as it applies to the *numerator* of Equation 3 (Savings Ration calculation), while Maintenance cost inflation is the inflation rate used in Equation 4 as it applies to the *denominator* of Equation 3. As shown in Figure 40, electricity costs must rise almost eight percent faster than maintenance costs in order to make a non-optimized alternative better than the "do nothing" alternative. This imbalance is unlikely to be sustained over the lifespan of the system.

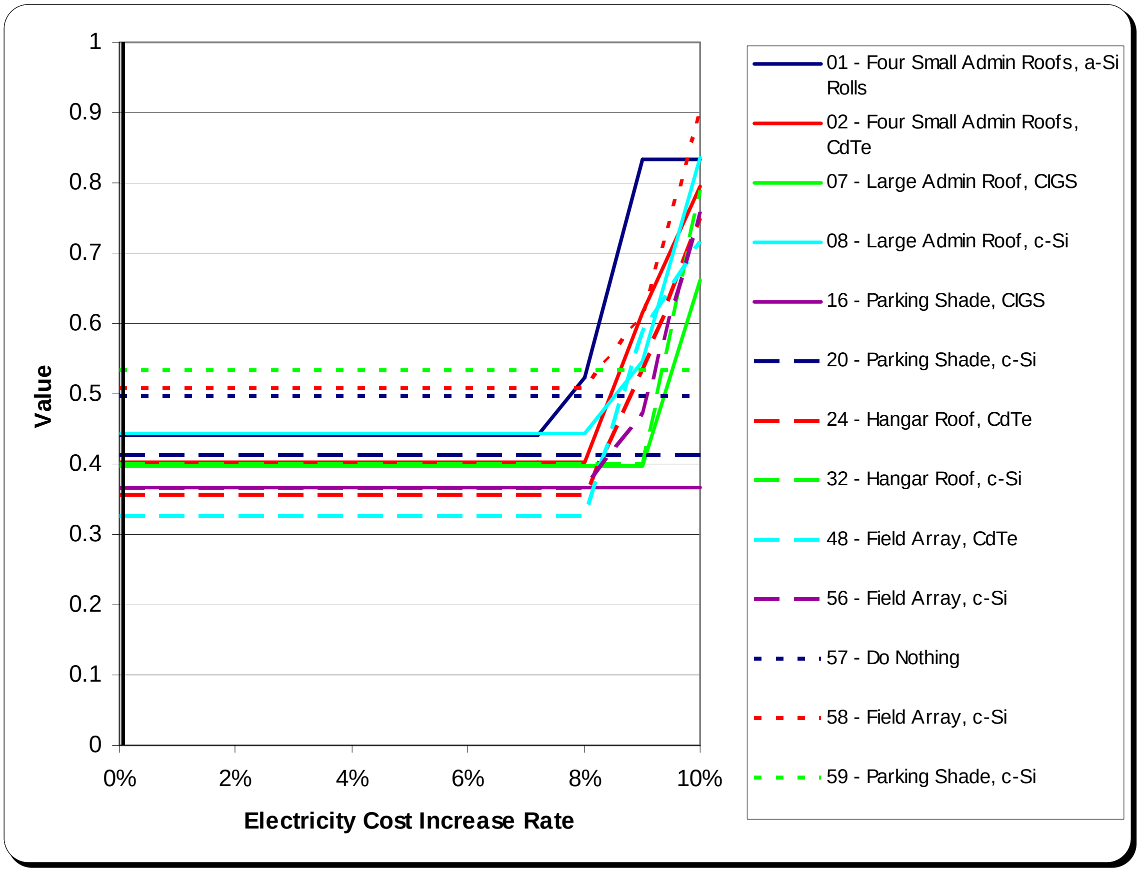


Figure 40: Sensitivity Analysis on Electricity Cost Increase Rate. A sensitivity analysis on the electricity cost increase rate shows that rankings only change if the cost of electricity rises eight percent faster than the cost of maintenance. In the deterministic analysis, the two costs are assumed to increase at the same rate.

Figure 41 evaluates the real cost of annual maintenance to see if it has an effect on rankings. The annual maintenance cost limits any change in ranking when the cost is greater than about \$4 / kW_p, but then, only when the cost of electricity has been inflated way beyond what Northern AFB paid in 2005 for electricity. When electricity can be purchased at \$0.023 / kWh, maintenance cost had no effect whatsoever, even when it was free. This is because the cost savings (benefit) from installing photovoltaics was smaller than its up-front and long-term costs. Increasing the long-term cost (maintenance cost)

only widened the gap further. Thus the Savings Ratio of any alternative remained below one and no alternative benefited from a rank change.

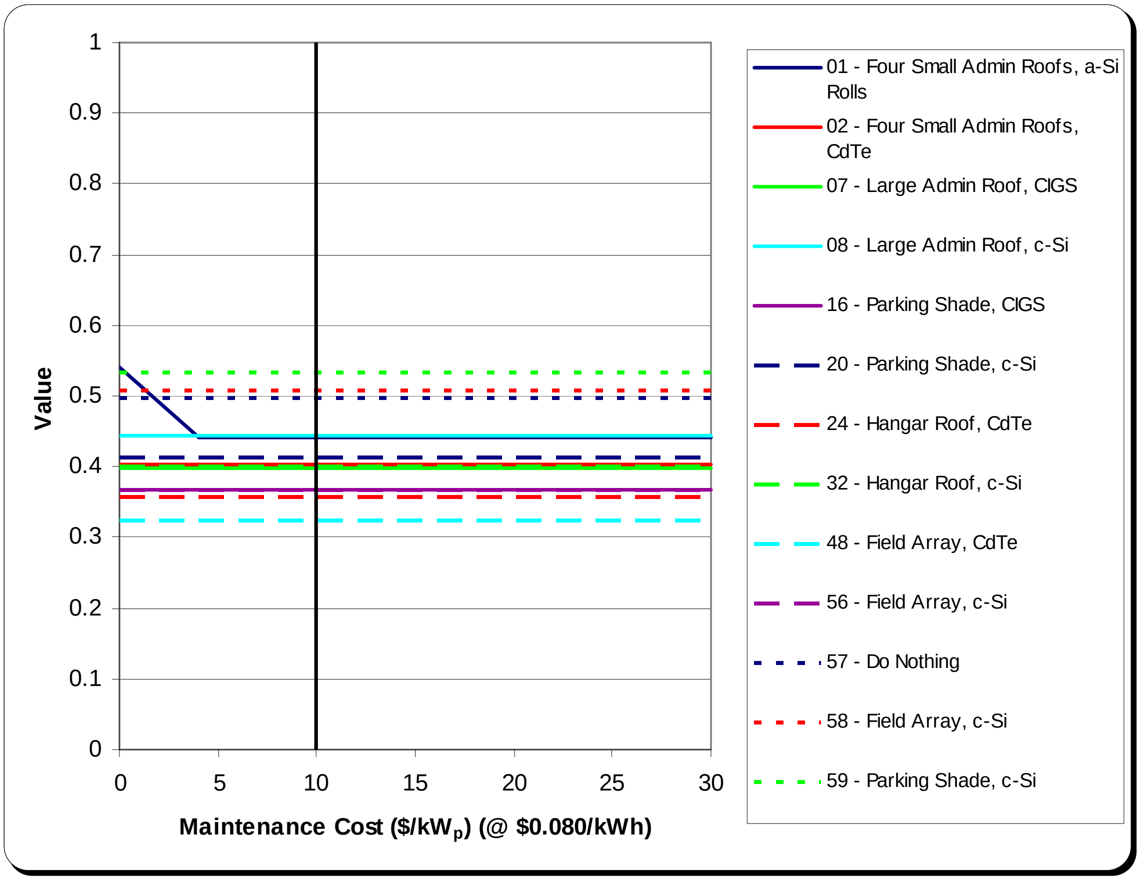


Figure 41: Sensitivity Analysis on Maintenance Cost. A sensitivity analysis on the cost of maintenance reveals the insignificant effect that maintenance cost has on the overall ranking. The black line represents the maintenance cost assumed in the deterministic analysis. Note that this analysis was generated while the electricity rate was $0.08 / kWh.

In Figure 42, an attempt is made to see if a drop in module costs will bring one of the photovoltaic alternatives to the top. However, because Northern AFB gets its electricity so inexpensively, even up to a cost reduction of 50 percent, the cost savings

cannot make up for structural, BOS component, and installation costs. There is no change in rankings within this range.

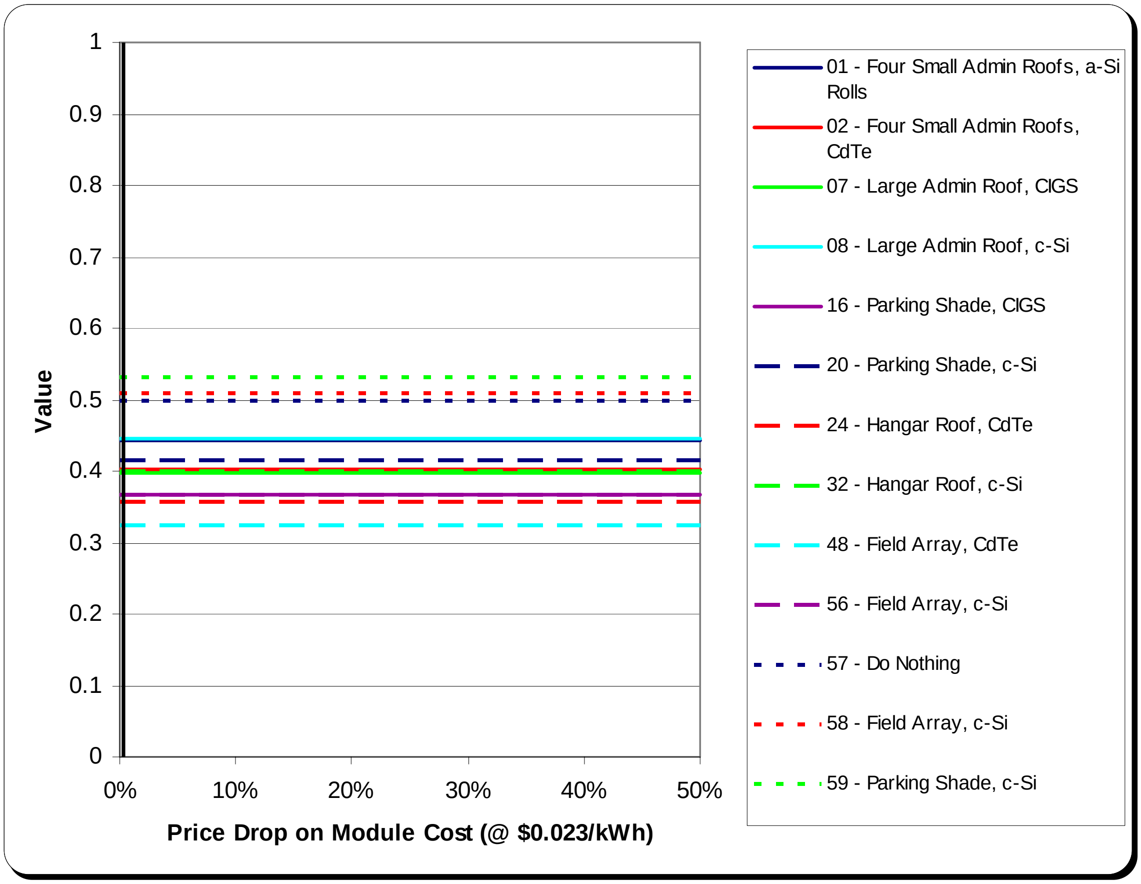


Figure 42: Sensitivity Analysis on Module Cost Price Decrease (at $0.023 / kWh). A sensitivity analysis on the price drop of photovoltaic modules shows that price reduction up to 50 percent have no effect on rank. This analysis uses the actual initial cost of electricity of $0.023 / kWh.

Figure 43 is the same analysis as Figure 42, only the cost of electricity is set at $0.08 / kWh instead of $0.023 / kWh. This time, cost decrease has a profound effect on the rankings. A change in ranking is seen after a module cost decrease of only eight percent. Around a 30 percent module cost decrease, several of the non-optimized

alternatives begin to outrank the "do nothing" alternative. This price decrease is largely anticipated within the next decade.

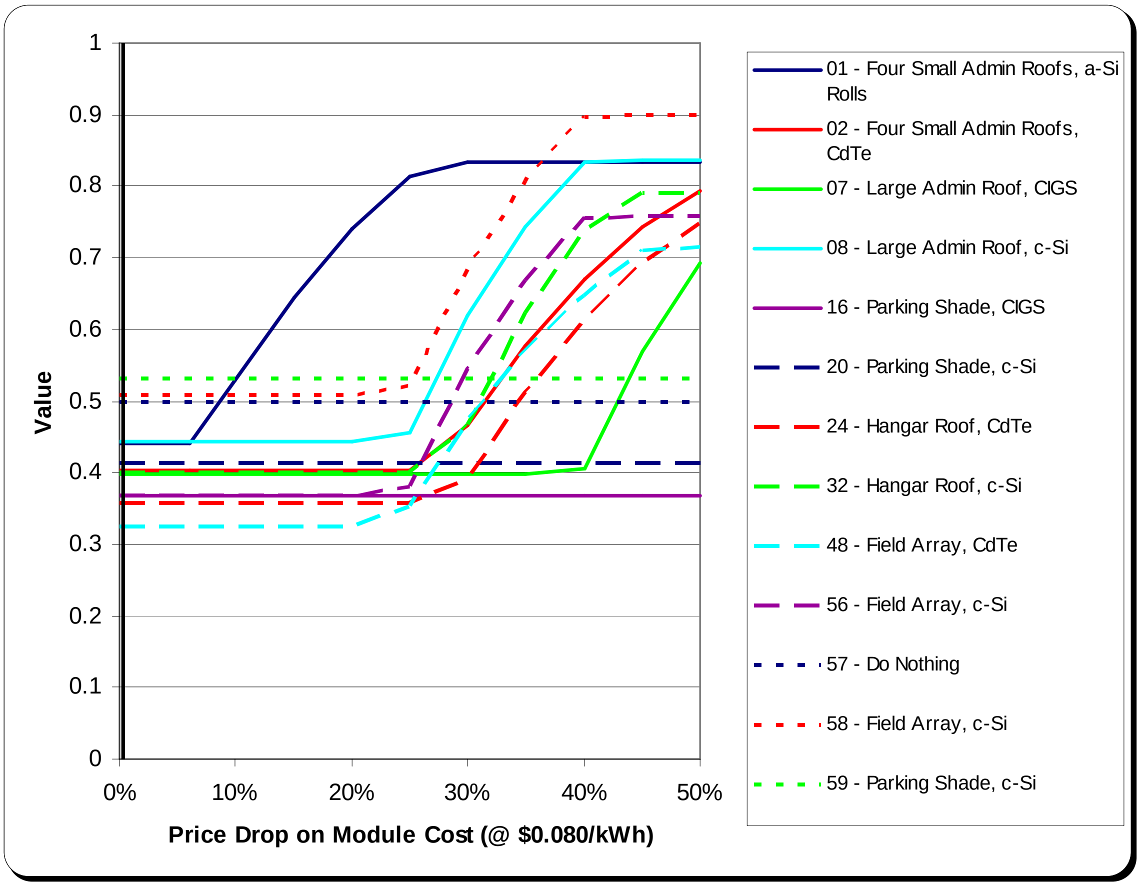


Figure 43: Sensitivity Analysis on Module Cost Price Decrease (at $0.08 / kWh). A sensitivity analysis on the price drop of photovoltaic modules shows that prices only have to drop about 8% to show a rank change, assuming an initial cost of electricity of $0.08 / kWh.

Once again, the effect of Northern AFB's inexpensive electricity can be seen in Figure 44 and Figure 45. No change in rankings is observed with a system longevity up to 50 years at the current low electricity rate (Figure 44).

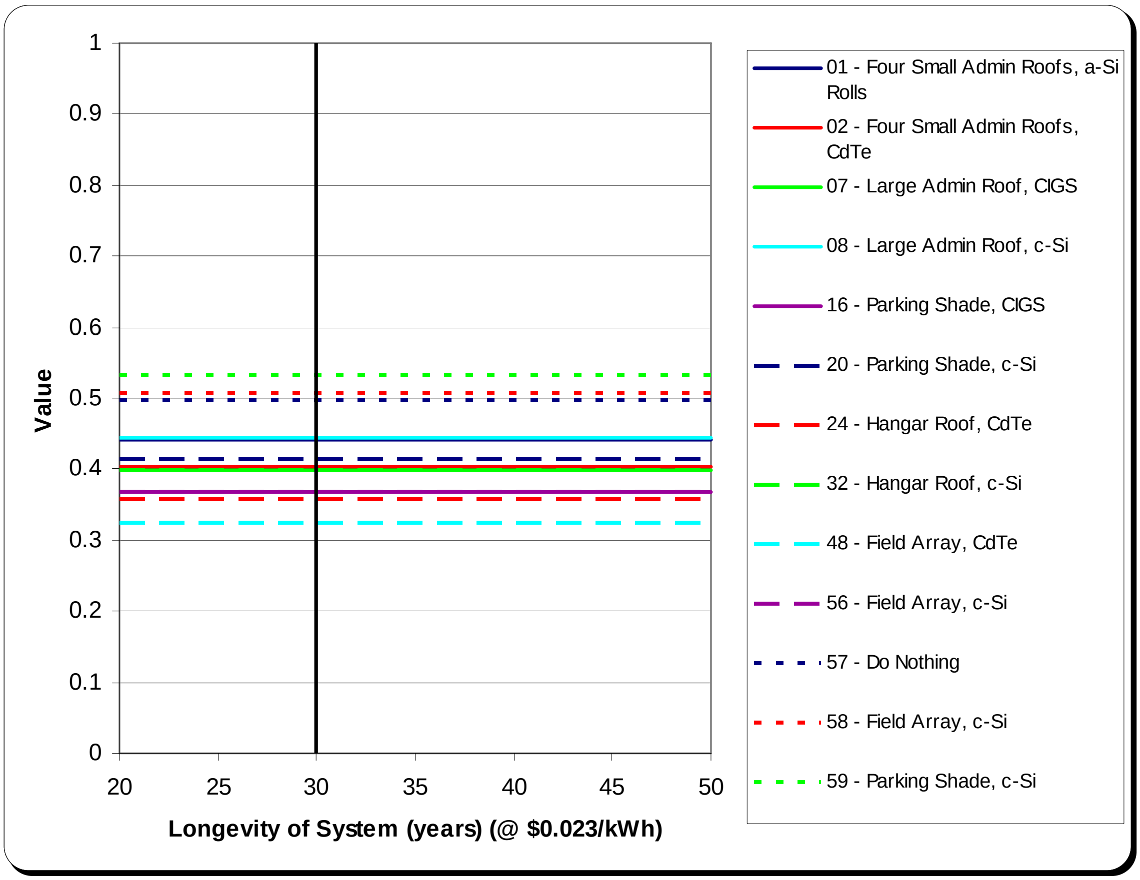


Figure 44: Sensitivity Analysis on Longevity of System (at $0.023 / kWh). A sensitivity analysis on how long the photovoltaic systems are expected to last shows no rank change up to 50 years. This analysis uses the initial cost of electricity of $0.023 / kWh. The black line represents the longevity assumed in the deterministic analysis.

However, if we assume the higher rate of $0.08 / kWh, then rankings change as early as a longevity of 33 years (Figure 45).

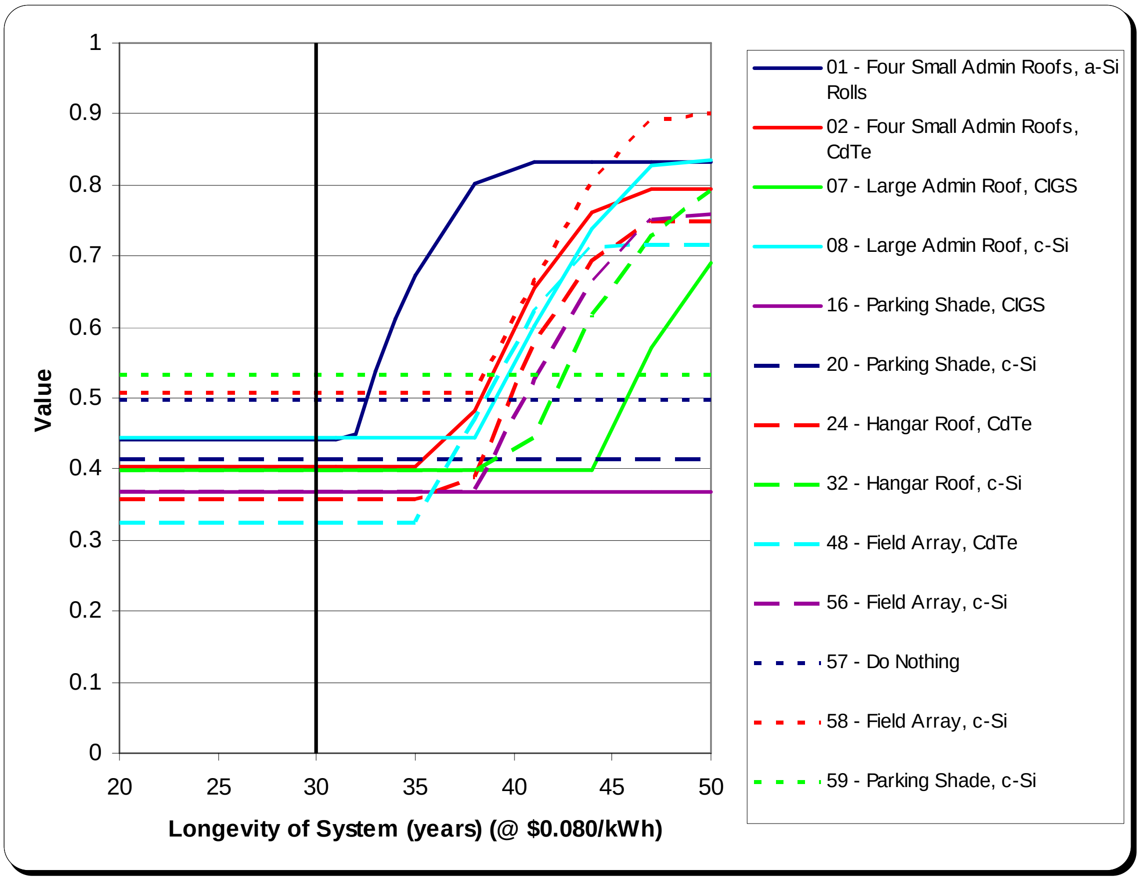


Figure 45: Sensitivity Analysis on Longevity of System (at $0.08 / kWh). A sensitivity analysis on how long the photovoltaic systems are expected to last shows a rank change around 33 years. This analysis uses an initial cost of electricity of $0.08 / kWh. The black line represents the longevity assumed in the deterministic analysis.

In all SDVF sensitivity analyses performed, the value of the "do nothing" alternative remained unchanged. This is because each of the analyses had an effect on the Savings Ratio, and in every analysis, the Savings Ratio of "do nothing" was unaffected, as was expected. Recall that the value of the Savings Ratio was zero for all alternatives in the deterministic analysis since the SDVF was increasing with a range of

1.0 to 1.2. Therefore, when the heavily weighted Savings Ratio was affected positively in the sensitivity analysis and became greater than one, it often had a profound effect on the overall ranking.

Throughout the sensitivity analysis on SDVFs, five non-optimized alternatives continuously ranked higher than the rest of the non-optimized alternatives. In alpha-numerical order, they were Alternative 01 (a-Si rolls on four small administrative-type buildings), Alternative 02 (CdTe panels on four small administrative-type buildings), Alternative 08 (c-Si panels on a large administrative-type roof), Alternative 48 (CdTe panels used in a field array), and Alternative 56 (c-Si panels used in a field array). Two alternatives performed consistently poorly. They were Alternative 16 (CIGS panels on a parking shade) and Alternative 20 (c-Si panels on a parking shade).

Of all the technologies, those alternatives utilizing c-Si tended to outperform similar placements with differing technologies. This is largely due to the higher efficiency of the c-Si modules, which permit a larger rated capacity for an equivalent physical array size. The alternative employing a-Si rolls also performed rather well. The advantages that a-Si rolls boast are low cost per rated capacity, negligible structural requirements, and low intrusivity. They also have virtually no impact on their developed or natural surroundings since their application is on otherwise unused roof space, and a-Si has been in production for a comparatively long time. Alternatives employing CdTe modules and CIGS modules tended to not fair as well in the sensitivity analysis. These two technologies are much newer and do not have the same lengthy track record as do the silicon-based modules.

Two sets of system placements ranked higher in the sensitivity analysis: four small administrative-type buildings, and field arrays. The advantages of smaller rooftop installations are their low structural requirements, low intrusivity, and unlikely need for NEPA actions. Field arrays capitalize on system size and economy of scale; however, they may lead to NEPA actions. Parking shade installations were the poorest fairing alternatives, except when optimized. They require a significant structural investment and may have an impact on the immediate developed and natural surroundings, triggering NEPA actions. It was also assumed that the modules are lying horizontally, so they never receive direct sunlight. A parking shade, however, has other intangible advantages not captured in this model.

It appears that the single most important factor influencing the rankings is the cost of electricity currently purchased from the grid. When grid electricity cost is high, the cost savings (benefit) realized by installing a photovoltaic system is greater, most likely leading to a Savings Ratio greater than one. However, when the grid electricity cost is low, the cost savings realized from the photovoltaic installation is small and, in the case of Northern AFB, the benefit is less than the long-term cost and the Savings Ratio becomes less than one. As long as Northern AFB continues to purchase electricity at its current low rate, non-optimized photovoltaic systems will have a difficult time competing. Even photovoltaic systems' redeeming features, such as their environmental benefits, cannot beat (in a value sense) the *status quo* when not optimized. However, the optimized systems performed remarkably well in all analyses.

5. Results and Conclusions

5.1. Introduction

This chapter will readdress the four research questions posed in Chapter 1. Then the chapter will address limitations and recommendations for future research. It will end with some final conclusions.

5.2. Research Summary

Four research questions were posed in Chapter 1. They are transcribed and briefly readdressed next.

- What are Air Force decision makers' objectives with respect to sources of electrical energy, and how does the decision maker value various aspects and qualities of photovoltaic technologies?

This question was addressed primarily through the development of the VFT decision model. Decision makers' values were determined through telephone and email conversations with SMEs who represented the decision makers' values. These values were categorized and organized into what became the value hierarchy. The values were also quantified with measures suggested by the SMEs. Decision makers, through their SMEs, expressed interest in renewable energy as an alternative to conventional energy; however, economic factors carry the greatest weight in the decision.

- How do retrofitted applications of photovoltaics perform in various regions of the country?

This question incorporates several elements of the model since *performance* is not necessarily based on electrical output alone. Some important factors involved in

performance include maintainability, complexity, and expected future performance as measured by past experience. However, perhaps the strongest measure of performance is addressed by the economic value of Savings Ratio. Naturally, photovoltaic systems in areas with greater solar radiation will likely provide greater electrical output, leading to a larger cost savings. However, as revealed by the sensitivity analysis, a major performance indicator is the local cost of electricity purchased off the grid. Higher costs lead to higher Savings Ratios, which, when they are above one, favor photovoltaics. It is also important to note that most of the alternatives examined in this research were not optimized and even involved measures at their worst-case levels. The two alternatives that were optimized performed very well relative to the *status quo*.

- How have multiple-objective decision models been used previously in the selection of energy sources?

Three multiple-objective, value-focused models each having to do with were reviewed in Chapter 2. The author of each model felt that the modeling technique employed was appropriate and useful. When selecting energy sources for a population, such as a military community, there is much to consider, and not every element is concrete. Multiple-objective models are well-suited to handle competing priorities, and value-focused models, in particular, are ideal for quantifying abstract concepts, such as environmental benefits and Intrusivity.

- What are the life cycle environmental burdens of photovoltaics?

The last part of Chapter 2 focused at length on the life cycle analysis aspects of photovoltaics. Photovoltaics return more energy than they consume, and their life cycle

has minimal, but still well-controlled emissions. The use of photovoltaics also carries other, intangible benefits under the guise of social obligations.

5.3. Research Limitations

The model has some limitations that should be identified. Some relate to the assumptions expressed in Chapter 1. First, the actual Savings Ratio realized after system installation is heavily dependent upon the true solar radiation at the installation site. This is impossible to predict precisely. Solar radiation could fluctuate considerably from the estimate, and the possibility exists that the Savings Ratio could end up being less than one when it was predicted to be greater than one. Second, the photovoltaic system may have had overwhelming support leading to its installation; however, personnel turnover may bring in leadership that is less supportive, resulting in budgetary cuts or other negative effects that affect the system's performance. A third limitation is related to the specific results from this analysis. First, 57 alternatives were revealed by employing a strategy table in Chapter 3 (the other two were developed separate from the strategy table). Normally, further analysis would have been accomplished on a set of alternatives that performed well; however, to make the analysis more interesting, a diverse set of 11 alternatives that represented a wide range of rankings was chosen. Further, three measures in the model involved details that were either very difficult to ascertain or were the same for every alternative and, thus, were not discriminators. Alternative scores corresponding to these measures were created in the interest of making the model more interesting. Additionally, certain data used by the model, especially technology-specific information, change rapidly. The alternative rankings presented in Chapter 4 should not be construed to be generally applicable at any installation. The future use of this model

will require situation-specific data to be researched by the analyst considering the decision. A final limitation is that the study does not consider the solar thermal value of the sun's energy and appropriate rooftop systems to harness this source. Solar thermal systems are indeed another excellent method of circumventing the slow carbon cycle by converting the sun's energy directly into usable heat. The best alternatives might combine photovoltaic and thermal energy into one system.

5.4. Recommendations for Future Research

This research has stimulated several ideas for future research in three main areas: decision models, pure research, and management. The simplest and least interesting concept for future research is to develop a similar model to identify other renewable alternatives, such as solar heating, passive solar retrofits, and wind energy. What might be more interesting is to apply a decision model of this type for the selection of energy sources in a deployed environment.

The second idea for future research was discovered while researching LCA data for photovoltaics. Huge amounts of data exist, but they are all reported in different units, with different assumptions, and in different contexts. Comparison and analysis of the data was difficult. A meta-analysis of the photovoltaic LCA literature could prove to be a very challenging and yet very rewarding task.

The last four ideas for future research concern various management themes and are largely political or policy-related. First is an analysis of the political ramifications of Air Force bases generating their own electricity. Bases are huge consumers of grid energy. If a customer as large as a base changes its usage drastically, it could have a profound

effect on the local utility's profits with a trickle-down effect. The utilities have a strong lobby in Washington DC and would probably have much to say about such a change.

Second, as one SME pointed out, when new power sources are added to the overall distribution system, unless consumption increases, another source must be removed from the grid. What would be the effect of increasing the supply side of the equation by adding more renewable energy when the utility company is not necessarily equipped to adapt quickly to the change?

Third, when private citizens want to add their small-scale green power system to the grid, they must ensure they have all the proper equipment installed to prevent shorting, spikes, and other damaging problems from propagating through the grid. These consumers' equipment must be under warranty, often, for up to 30 years, and the consumers must also carry hefty insurance policies in the event of a problem. This question was also raised by an SME: does the Air Force want to assume a risk so great when they connect their massive renewable systems to the grid, particularly when the scale is so much larger? What other options are available?

Finally, their may be an adverse public response from sectors of the population when the federal government spends tax funds on renewable systems that may or may not provide payback and have not run long enough to prove their worth. Should renewable energy systems be funded by the public sector or only by the private sector?

5.5. Final Conclusions

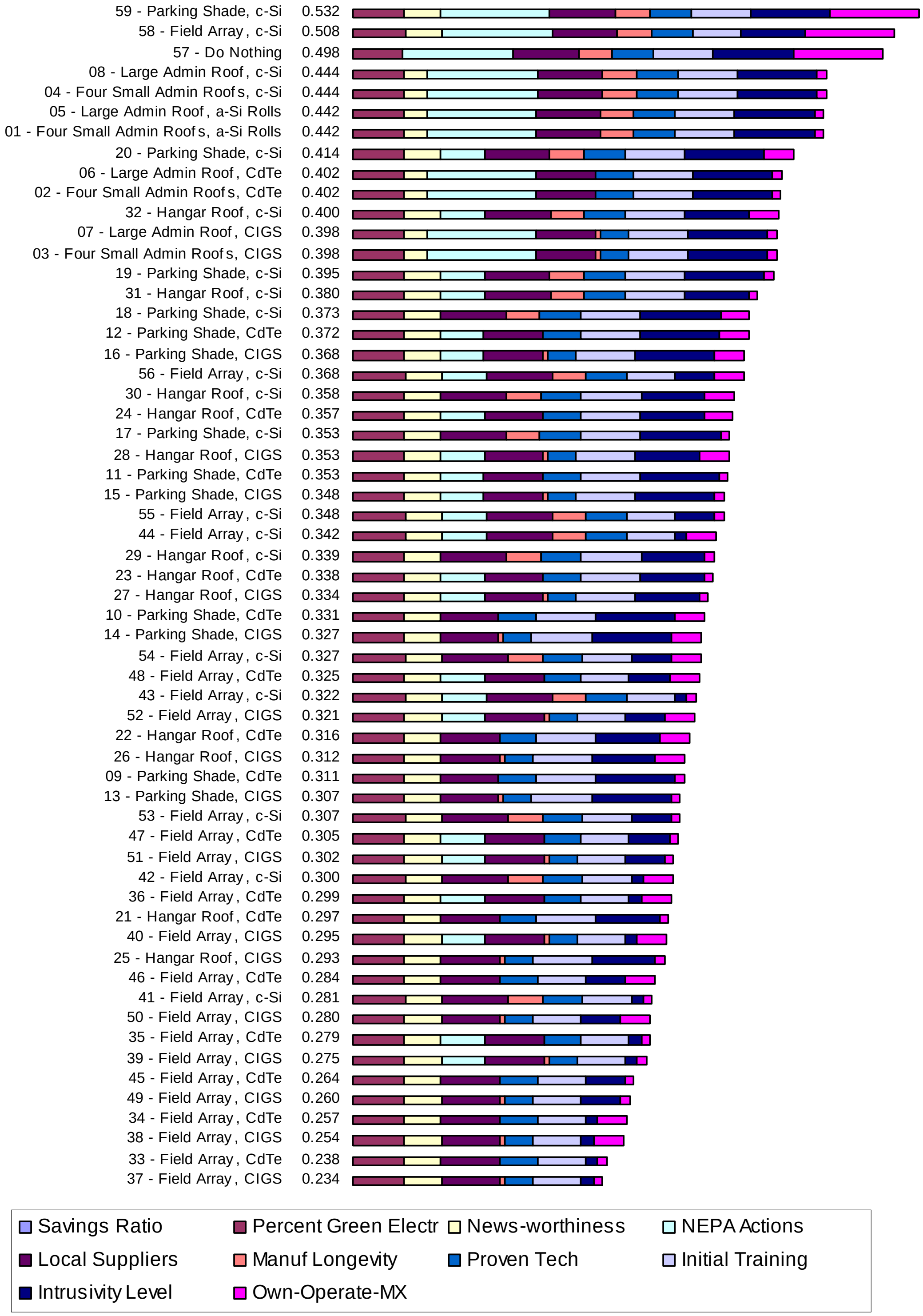
This research developed a well-rounded decision model to help Air Force decision makers choose the best photovoltaic alternative at their installations. The model hierarchy was designed based on input from several SMEs located at three geographically

diverse Air Force bases. The model analysis was based on the SDVFs and weighting of only one base; it can be equally as effective at other bases or even at a higher headquarters level. Overall, photovoltaic technologies have the potential to compete successfully with the *status quo*. Several factors influence photovoltaics performance, most importantly, the current cost of electricity supplied off the grid. This research biased heavily against photovoltaics in three ways: first, the Air Force base used in the analysis is in the northern part of the continental US, and it does not benefit from the intense solar radiation that southern bases enjoy; second, the base chosen also has very low grid electricity costs; and third, most of the alternatives, in fact all alternatives revealed by the strategy table, were suboptimal to fully stress the model. Anticipated module cost reductions will help make photovoltaic technologies an obvious choice for providing renewable electricity, especially where grid-supplied electricity is expensive.

Appendix A: All Alternatives Revealed by the Strategy Table

Alternative Name	*Intrusivity Level*	*NEPA Actions*	*Own-Operate-MX*
01 - Four Small Admin Roofs, a-Si Rolls	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
02 - Four Small Admin Roofs, CdTe	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
03 - Four Small Admin Roofs, CIGS	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
04 - Four Small Admin Roofs, c-Si	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
05 - Large Admin Roof, a-Si Rolls	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
06 - Large Admin Roof, CdTe	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
07 - Large Admin Roof, CIGS	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
08 - Large Admin Roof, c-Si	Rooftops not Near Flightline or N/A	CATEX or N/A	AF-AF-AF
09 - Parking Shade, CdTe	Rooftops not Near Flightline or N/A	EIS	AF-AF-AF
10 - Parking Shade, CdTe	Rooftops not Near Flightline or N/A	EIS	AF-KTR-KTR
11 - Parking Shade, CdTe	Rooftops not Near Flightline or N/A	EA FONPA	AF-AF-AF
12 - Parking Shade, CdTe	Rooftops not Near Flightline or N/A	EA FONPA	AF-KTR-KTR
13 - Parking Shade, CIGS	Rooftops not Near Flightline or N/A	EIS	AF-AF-AF
14 - Parking Shade, CIGS	Rooftops not Near Flightline or N/A	EIS	AF-KTR-KTR
15 - Parking Shade, CIGS	Rooftops not Near Flightline or N/A	EA FONPA	AF-AF-AF
16 - Parking Shade, CIGS	Rooftops not Near Flightline or N/A	EA FONPA	AF-KTR-KTR
17 - Parking Shade, c-Si	Rooftops not Near Flightline or N/A	EIS	AF-AF-AF
18 - Parking Shade, c-Si	Rooftops not Near Flightline or N/A	EIS	AF-KTR-KTR
19 - Parking Shade, c-Si	Rooftops not Near Flightline or N/A	EA FONPA	AF-AF-AF
20 - Parking Shade, c-Si	Rooftops not Near Flightline or N/A	EA FONPA	AF-KTR-KTR
21 - Hangar Roof, CdTe	Rooftops Near Flightline	EIS	AF-AF-AF
22 - Hangar Roof, CdTe	Rooftops Near Flightline	EIS	AF-KTR-KTR
23 - Hangar Roof, CdTe	Rooftops Near Flightline	EA FONPA	AF-AF-AF
24 - Hangar Roof, CdTe	Rooftops Near Flightline	EA FONPA	AF-KTR-KTR
25 - Hangar Roof, CIGS	Rooftops Near Flightline	EIS	AF-AF-AF
26 - Hangar Roof, CIGS	Rooftops Near Flightline	EIS	AF-KTR-KTR
27 - Hangar Roof, CIGS	Rooftops Near Flightline	EA FONPA	AF-AF-AF
28 - Hangar Roof, CIGS	Rooftops Near Flightline	EA FONPA	AF-KTR-KTR
29 - Hangar Roof, c-Si	Rooftops Near Flightline	EIS	AF-AF-AF
30 - Hangar Roof, c-Si	Rooftops Near Flightline	EIS	AF-KTR-KTR
31 - Hangar Roof, c-Si	Rooftops Near Flightline	EA FONPA	AF-AF-AF
32 - Hangar Roof, c-Si	Rooftops Near Flightline	EA FONPA	AF-KTR-KTR
33 - Field Array, CdTe	Grnd, Inhabited Area, Flightline	EIS	AF-AF-AF
34 - Field Array, CdTe	Grnd, Inhabited Area, Flightline	EIS	AF-KTR-KTR
35 - Field Array, CdTe	Grnd, Inhabited Area, Flightline	EA FONPA	AF-AF-AF
36 - Field Array, CdTe	Grnd, Inhabited Area, Flightline	EA FONPA	AF-KTR-KTR
37 - Field Array, CIGS	Grnd, Inhabited Area, Flightline	EIS	AF-AF-AF
38 - Field Array, CIGS	Grnd, Inhabited Area, Flightline	EIS	AF-KTR-KTR
39 - Field Array, CIGS	Grnd, Inhabited Area, Flightline	EA FONPA	AF-AF-AF
40 - Field Array, CIGS	Grnd, Inhabited Area, Flightline	EA FONPA	AF-KTR-KTR
41 - Field Array, c-Si	Grnd, Inhabited Area, Flightline	EIS	AF-AF-AF
42 - Field Array, c-Si	Grnd, Inhabited Area, Flightline	EIS	AF-KTR-KTR
43 - Field Array, c-Si	Grnd, Inhabited Area, Flightline	EA FONPA	AF-AF-AF
44 - Field Array, c-Si	Grnd, Inhabited Area, Flightline	EA FONPA	AF-KTR-KTR
45 - Field Array, CdTe	Grnd, Inhabited Area	EIS	AF-AF-AF
46 - Field Array, CdTe	Grnd, Inhabited Area	EIS	AF-KTR-KTR
47 - Field Array, CdTe	Grnd, Inhabited Area	EA FONPA	AF-AF-AF
48 - Field Array, CdTe	Grnd, Inhabited Area	EA FONPA	AF-KTR-KTR
49 - Field Array, CIGS	Grnd, Inhabited Area	EIS	AF-AF-AF
50 - Field Array, CIGS	Grnd, Inhabited Area	EIS	AF-KTR-KTR
51 - Field Array, CIGS	Grnd, Inhabited Area	EA FONPA	AF-AF-AF
52 - Field Array, CIGS	Grnd, Inhabited Area	EA FONPA	AF-KTR-KTR
53 - Field Array, c-Si	Grnd, Inhabited Area	EIS	AF-AF-AF
54 - Field Array, c-Si	Grnd, Inhabited Area	EIS	AF-KTR-KTR
55 - Field Array, c-Si	Grnd, Inhabited Area	EA FONPA	AF-AF-AF
56 - Field Array, c-Si	Grnd, Inhabited Area	EA FONPA	AF-KTR-KTR
57 - Do Nothing	Rooftops not Near Flightline or N/A	CATEX or N/A	UTIL-UTIL-UTIL

Appendix B: Ranking of All Alternatives



Appendix C: Assumptions and Calculation Sheet

A	B	C	D	E	F	G	H	I	J	K	L	M
				E_{sloped}: (0.9*C/2)/cos(roof slope)								
				E_{flat}: 0.9*C							I*K	
		B*.0929		E_{curved}: (0.9*C*pi)/8						int(F/(G*H))		L/F
	Building Size (SF)	Building Size (m^2)	Roof Type	System Size per Building (m^2)	System Size Total (m^2)	Module Length (m)	Module Width (m)	Module Weight (kg)	Rated Module Power (W_p)	Number of Modules	Total Weight (kg)	Weight per Area (kg/m^2)
Four Small Admin Roofs, a-Si Rolls	2000	186	sloped	118	473	5.486	0.394	7.7	136	218	1679	3.55
Four Small Admin Roofs, CdTe	2000	186	sloped	118	473	1.200	0.600	11.4	65	656	7478	15.81
Four Small Admin Roofs, CIGS	2000	186	sloped	118	473	1.205	0.605	12.6	80	648	8165	17.26
Four Small Admin Roofs, c-Si	2000	186	sloped	118	473	1.559	0.798	16.0	210	380	6080	12.85
Large Admin Roof, a-Si Rolls	8000	743	flat	669	669	5.486	0.394	7.7	136	309	2379	3.56
Large Admin Roof, CdTe	8000	743	flat	669	669	1.200	0.600	11.4	65	929	10591	15.83
Large Admin Roof, CIGS	8000	743	flat	669	669	1.205	0.605	12.6	80	917	11554	17.27
Large Admin Roof, c-Si	8000	743	flat	669	669	1.559	0.798	16.0	210	537	8592	12.85
Parking Shade, CdTe	12920	1200	flat	1080	1080	1.200	0.600	11.4	65	1500	17100	15.83
Parking Shade, CIGS	12920	1200	flat	1080	1080	1.205	0.605	12.6	80	1481	18661	17.27
Parking Shade, c-Si	12920	1200	flat	1080	1080	1.559	0.798	16.0	210	868	13888	12.86
Hangar Roof, CdTe	60550	5625	curved*	1988	1988	1.200	0.600	11.4	65	2761	31475	15.83
Hangar Roof, CIGS	60550	5625	curved*	1988	1988	1.205	0.605	12.6	80	2727	34360	17.28
Hangar Roof, c-Si	60550	5625	curved*	1988	1988	1.559	0.798	16.0	210	1598	25568	12.86
Field Array, CdTe	n/a	n/a	n/a	4000	4000	1.200	0.600	11.4	65	5555	63327	15.83
Field Array, CIGS	n/a	n/a	n/a	4000	4000	1.205	0.605	12.6	80	5486	69124	17.28
Field Array, c-Si	n/a	n/a	n/a	4000	4000	1.559	0.798	16.0	210	3215	51440	12.86
Do Nothing	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0	0.00

*1/3 of Rated Output	PVWATTS Annual AC Energy (kWh)		
	23^0	45^0	67^0
59.8	81427	84109	77038
72.7	98993	102253	93657
111.9	152370	157387	144156

A	N	O	P	Q	R	S	T	U	V
	J*K/1000		O*P20		Q*K				
	Rated System Output (kW_p)	PVWATTS Annual AC Energy (kWh)	PVWATTS Annual Savings ($)	Labor ($/module)	Module Labor Total ($)	Site Constr Total ($)	Primary Support Structure Total ($)	Secondary Support Structure Total ($)	Electrical Components Total ($)
Four Small Admin Roofs, a-Si Rolls	29.6	41632	$ 958	$ 35	$ 7,691	$ -	$ -	$ -	$ 4,390
Four Small Admin Roofs, CdTe	42.6	59917	$ 1,378	$ 35	$ 23,144	$ -	$ -	$ 23,144	$ 4,390
Four Small Admin Roofs, CIGS	51.8	72857	$ 1,676	$ 35	$ 22,861	$ -	$ -	$ 22,861	$ 4,390
Four Small Admin Roofs, c-Si	79.8	112239	$ 2,581	$ 35	$ 13,406	$ -	$ -	$ 13,406	$ 4,390
Large Admin Roof, a-Si Rolls	42.0	59142	$ 1,360	$ 35	$ 10,902	$ -	$ -	$ -	$ 1,098
Large Admin Roof, CdTe	60.4	85052	$ 1,956	$ 35	$ 32,775	$ -	$ -	$ 32,775	$ 1,098
Large Admin Roof, CIGS	73.4	103358	$ 2,377	$ 35	$ 32,352	$ -	$ -	$ 32,352	$ 1,098
Large Admin Roof, c-Si	112.8	158839	$ 3,653	$ 35	$ 18,945	$ -	$ -	$ 18,945	$ 1,098
Parking Shade, CdTe	97.5	109503	$ 2,519	$ 35	$ 52,920	$ -	$ 168,027	$ 52,920	$ 1,098
Parking Shade, CIGS	118.5	133088	$ 3,061	$ 35	$ 52,250	$ -	$ 168,027	$ 52,250	$ 1,098
Parking Shade, c-Si	182.3	204742	$ 4,709	$ 35	$ 30,623	$ -	$ 168,027	$ 30,623	$ 1,098
Hangar Roof, CdTe	179.5	242574	$ 5,579	$ 35	$ 97,408	$ -	$ -	$ 97,408	$ 1,098
Hangar Roof, CIGS	218.2	294903	$ 6,783	$ 35	$ 96,209	$ -	$ -	$ 96,209	$ 1,098
Hangar Roof, c-Si	335.6	453913	$ 10,440	$ 35	$ 56,377	$ -	$ -	$ 56,377	$ 1,098
Field Array, CdTe	361.1	508483	$ 11,695	$ 35	$ 195,980	$ 4,613	$ -	$ 195,980	$ 1,098
Field Array, CIGS	438.9	618037	$ 14,215	$ 35	$ 193,546	$ 4,613	$ -	$ 193,546	$ 1,098
Field Array, c-Si	675.2	950782	$ 21,868	$ 35	$ 113,425	$ 4,613	$ -	$ 113,425	$ 1,098
Do Nothing	0.0	0	$ -	$ -	$ -	$ -	$ -	$ -	$ -

Cost per kWh ($)
$ 0.023

A	W	X	Y	Z	AA	AB	AC	AD	AE	AF
	S+T+U+V+R		X*N+W		Z*N				FV(AB,AD,-P)/(Y+FV(AC,AD,-AA))	
	Special Constr Cost ($)	Module Purchase Cost ($/kW$_p$)	Install Cost ($)	Annual MX Cost ($/kW$_p$)	Annual MX Cost ($)	Elect Cost Increase Rate	MX Cost Increase Rate	Lifespan (yrs)	Savings Ratio	Total Electricity (kWh)
Four Small Admin Roofs, a-Si Rolls	$ 12,081	$ 2,860	$ 96,875	$ 10	$ 296	0.0%	0.0%	30	0.27	74037572
Four Small Admin Roofs, CdTe	$ 50,678	$ 2,600	$ 161,542	$ 10	$ 426	0.0%	0.0%	30	0.24	74037572
Four Small Admin Roofs, CIGS	$ 50,113	$ 3,630	$ 238,292	$ 10	$ 518	0.0%	0.0%	30	0.20	74037572
Four Small Admin Roofs, c-Si	$ 31,203	$ 3,630	$ 320,877	$ 10	$ 798	0.0%	0.0%	30	0.22	74037572
Large Admin Roof, a-Si Rolls	$ 11,999	$ 2,600	$ 121,262	$ 10	$ 420	0.0%	0.0%	30	0.30	74037572
Large Admin Roof, CdTe	$ 66,648	$ 2,600	$ 223,649	$ 10	$ 604	0.0%	0.0%	30	0.24	74037572
Large Admin Roof, CIGS	$ 65,801	$ 3,630	$ 332,098	$ 10	$ 734	0.0%	0.0%	30	0.20	74037572
Large Admin Roof, c-Si	$ 38,988	$ 3,630	$ 448,343	$ 10	$ 1,128	0.0%	0.0%	30	0.23	74037572
Parking Shade, CdTe	$ 274,964	$ 2,600	$ 528,464	$ 10	$ 975	0.0%	0.0%	30	0.14	74037572
Parking Shade, CIGS	$ 273,624	$ 3,630	$ 703,706	$ 10	$ 1,185	0.0%	0.0%	30	0.12	74037572
Parking Shade, c-Si	$ 230,371	$ 3,630	$ 892,047	$ 10	$ 1,823	0.0%	0.0%	30	0.15	74037572
Hangar Roof, CdTe	$ 195,914	$ 2,600	$ 662,523	$ 10	$ 1,795	0.0%	0.0%	30	0.23	74037572
Hangar Roof, CIGS	$ 193,515	$ 3,630	$ 985,436	$ 10	$ 2,182	0.0%	0.0%	30	0.19	74037572
Hangar Roof, c-Si	$ 113,852	$ 3,630	$ 1,332,008	$ 10	$ 3,356	0.0%	0.0%	30	0.22	74037572
Field Array, CdTe	$ 397,672	$ 2,600	$ 1,336,467	$ 10	$ 3,611	0.0%	0.0%	30	0.24	74037572
Field Array, CIGS	$ 392,803	$ 3,630	$ 1,985,937	$ 10	$ 4,389	0.0%	0.0%	30	0.20	74037572
Field Array, c-Si	$ 232,561	$ 3,630	$ 2,683,356	$ 10	$ 6,752	0.0%	0.0%	30	0.23	74037572
Do Nothing	$ -	$ -	$ -	$ -	$ -	0.0%	0.0%	30	1.00	74037572

A	AG	AH
		(O+AG*(AF-O))/AF
	Initial % Green Electricity	Final % Green Electricity
Four Small Admin Roofs, a-Si Rolls	17.58%	17.62%
Four Small Admin Roofs, CdTe	17.58%	17.64%
Four Small Admin Roofs, CIGS	17.58%	17.66%
Four Small Admin Roofs, c-Si	17.58%	17.70%
Large Admin Roof, a-Si Rolls	17.58%	17.64%
Large Admin Roof, CdTe	17.58%	17.67%
Large Admin Roof, CIGS	17.58%	17.69%
Large Admin Roof, c-Si	17.58%	17.75%
Parking Shade, CdTe	17.58%	17.70%
Parking Shade, CIGS	17.58%	17.72%
Parking Shade, c-Si	17.58%	17.80%
Hangar Roof, CdTe	17.58%	17.85%
Hangar Roof, CIGS	17.58%	17.90%
Hangar Roof, c-Si	17.58%	18.08%
Field Array, CdTe	17.58%	18.14%
Field Array, CIGS	17.58%	18.26%
Field Array, c-Si	17.58%	18.63%
Do Nothing	17.58%	17.58%

Appendix D: Calculation of Change in Percent Green Energy

The following is the calculation of the change in Percent Green Energy from before photovoltaic system installation to after installation. The value in 'G' is not the value used in the measure. The measure uses the value in 'F'.

BEFORE PHOTOVOLTAIC SYSTEM INSTALLATION			Source / Calculation
A	Total Electrical Consumption (Grid and Otherwise)	1000 MWh	from Records
B	Amount of 'A' from Green Sources (Initial)	20 MWh	from Records
C	Percent of 'A' that is Green Electricity (Initial)	2.000%	B/A

PHOTOVOLTAIC SYSTEM INSTALLED			
D	Average Photovoltaic System Output	0.5 MWh	from PVWATTS

AFTER PHOTOVOLTAIC SYSTEM INSTALLATION			
E	Amount of 'A' from Green Sources (Final)	20.49 MWh	D+C*(A-D)
F	Percent of 'A' that is Green Electricity (Final)	2.049%	E/A

DIFFERENCE			
G	Change in Green Electricity Consumed	2.450%	(F-C)/C

Appendix E: “Local Suppliers” Measure Procedure

Steps to Navigate Momentum Technologies, LLC, Source Guides to Find Parts Suppliers (Momentum Technologies LLC, 2005)**:**

1. Go to http://www.sourceguides.com/index.html
2. Click on “The Source for Renewable Energy”
3. Click on “Renewable Energy Businesses”
4. Click on “Renewable Energy Businesses in the World by Product Type”
5. Click on “Solar Energy Businesses in the World”
6. Click on “Solar Energy Businesses in the World by Type of Solar Energy Product”
7. Click on “Photovoltaic System Businesses in the World”
8. Click on “Photovoltaic System Businesses in the World by Business Type”
9. Click on “Photovoltaic System Retail Businesses in the World”
10. Click on “Photovoltaic System Retail Businesses in the World by Location”
11. Click on “Photovoltaic System Retail Businesses in the United States”
12. Click on “Photovoltaic System Retail Businesses in the United States by State”
13. Click on the appropriate state or states within the defined radius
14. Check the address of each business and count the number of suppliers within the defined radius

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Vita

Captain Mostyn O. Kellner graduated from Keene High School in Keene, New Hampshire. He entered undergraduate studies at the University of New Hampshire in Durham, New Hampshire, where he graduated with a Bachelor of Science degree in Civil Engineering in May 1999. He was commissioned through AFROTC Detachment 475 at the University of New Hampshire.

His first assignment was at McGuire AFB, New Jersey, where he served as the Executive Officer of the 305th Operations Support Squadron. In August 2000, he was transferred to Laughlin AFB, Texas, and served as a student in Undergraduate Pilot Training. In February 2001, he was assigned to Moody AFB, Georgia, where he served both as Project Engineer and as Readiness Flight Commander in the 347th Civil Engineer Squadron and as Officer-in-Charge of the Plans Office at the 347th Mission Support Group. He deployed overseas in January 2003 in support of Operations ENDURING FREEDOM and IRAQI FREEDOM. In August 2004, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to Pope AFB, North Carolina.

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14. ABSTRACT
The United States is currently consuming fossil fuels faster than natural processes can replace them. Our nation's leaders recognize that a diverse energy portfolio including renewable energy is the key to maintaining our economy, security, and the environment. The federal government is by far the greatest energy consumer; thus, our nation's leaders have directed federal agencies to strive to increase the use of renewable energy at federal facilities. Solar electricity technologies, in the form of photovoltaics, have great potential in the renewable energy mix. Although a major strategy should be integrating photovoltaics into the design of new facilities, an important early consideration should be the installation of photovoltaic modules in open areas and/or module retrofits onto existing structures. This research developed a model based on decision makers' value systems to quantify and rank several photovoltaic technologies. The goal of the model was to determine what alternatives would most align with Air Force energy and environmental objectives. After working with subject matter experts at three bases, a comprehensive hierarchy was developed. This hierarchy was then used to find the best alternatives at one base. It was found that photovoltaic technologies may indeed successfully compete with grid-supplied electricity when utilizing a value-focused approach.

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